Unit 1

Physical Quantities and Measurement

STUDENT'S LEARNING OUTCOMES

After studying this unit, the students will be able to:

- describe the crucial role of Physics in Science, Technology and Society.
- explain with examples that Science is based on physical quantities which consist of numerical magnitude and a unit.
- differentiate between base and derived physical quantities.
- list the seven units of System International (SI) alongwith their symbols and physical quantities (standard definitions of SI units are not required).
- interconvert the prefixes and their symbols to indicate multiples and sub-multiples for both base and derived units.
- write the answer in scientific notation in measurements and calculations.
- describe the working of Vernier Callipers and screw gauge for measuring length.
- identify and explain the limitations of measuring instruments such as metre rule, Vernier Callipers and screw gauge.
- describe the need using significant figures for recording and stating results in the laboratory.

This unit is built on

Measurement

-Science-VIII

Scientific Notation

-Maths-IX

This unit leads to:

Measurement

-Physics-XI

Major Concepts

1.1 Introduction to Physics
1.2 Physical quantities
1.3 International System of units
1.4 Prefixes (multiples and sub-multiples)
1.5 Scientific notation/ Standard form
1.6 Measuring instruments
- metre rule
- Vernier Callipers
- screw gauge
- physical balance
- stopwatch
- measuring cylinder

1.7 An introduction to significant figures

When you can measure what you are speaking about and express it in numbers, you know something about it. When you cannot measure what you are speaking about or you cannot express it in numbers, your knowledge is of a meagre and of unsatisfactory kind.

Lord Kelvin

FOR YOUR INFORMATION

Andromeda is one of the billions of galaxies of known universe.

INVESTIGATION SKILLS

The students will be able to:

- compare the least count/ accuracy of the following measuring instruments and state their measuring range:
  - (i) Measuring tape
  - (ii) Metre rule
  - (iii) Vernier Callipers
  - (iv) Micrometer screw gauge
- make a paper scale of given least count e.g. 0.2 cm and 0.5 cm.
- determine the area of cross section of a solid cylinder with Vernier Callipers and screw gauge and evaluate which measurement is more precise.
- determine an interval of time using stopwatch.
- determine the mass of an object by using different types of balances and identify the most accurate balance.
- determine volume of an irregular shaped object using a measuring cylinder.
- List safety equipments and rules.
- Use appropriate safety equipments in laboratory.

SCIENCE, TECHNOLOGY AND SOCIETY CONNECTION

The students will be able to:

- determine length, mass, time and volume in daily life activities using various measuring instruments.
- list with brief description the various branches of physics.

Man has always been inspired by the wonders of nature. He has always been curious to know the secrets of nature and remained in search of the truth and reality. He observes various phenomena and tries to find their answers by logical reasoning. The knowledge gained through observations and

experimentations is called Science. The word science is derived from the Latin word scientia, which means knowledge. Not until eighteenth century, various aspect of material objects were studied under a single subject called natural philosophy. But as the knowledge increased, it was divided into two main streams; Physical sciences — which deal with the study of non-living things and Biological sciences — which are concerned with the study of living things.

Measurements are not confined to science. They are part of our lives. They play an important role to describe and understand the physical world. Over the centuries, man has improved the methods of measurements. In this unit, we will study some of physical quantities and a few useful measuring instruments. We will also learn the measuring techniques that enable us to measure various quantities accurately.

1.1 INTRODUCTION TO PHYSICS

In the nineteenth century, physical sciences were divided into five distinct disciplines; physics, chemistry, astronomy, geology and meteorology. The most fundamental of these is the Physics. In Physics, we study matter, energy and their interaction. The laws and principles of Physics help us to understand nature.

The rapid progress in science during the recent years has become possible due to the discoveries and inventions in the field of Physics. The technologies are the applications of scientific principles. Most of the technologies of our modern society throughout the world are related to Physics. For example, a car is made on the principles of mechanics and a refrigerator is based on the principles of thermodynamics.

In our daily life, we hardly find a device where Physics is not involved. Consider pulleys that make it easy to lift heavy loads. Electricity is used not only to

BRANCHES OF PHYSICS

Mechanics:
It is the study of motion of objects, its causes and effects.

Heat:
It deals with the nature of heat, modes of transfer and effects of heat.

Sound:
It deals with the physical aspects of sound waves, their production, properties and applications.

Light (Optics):
It is the study of physical aspects of light, its properties, working and use of optical instruments.

Electricity and Magnetism:
It is the study of the charges at rest and in motion, their effects and their relationship with magnetism.

Atomic Physics:
It is the study of the structure and properties of atoms.

Nuclear Physics:
It deals with the properties and behaviour of nuclei and the particles within the nuclei.

Plasma Physics:
It is the study of production, properties of the ionic state of matter - the fourth state of matter.

Geophysics:
It is the study of the internal structure of the Earth.

(a) (b)

Figure 1.1 (a) a vacuum cleaner
(b) a mobile phone

DO YOU KNOW?

Wind turbines are used to produce pollution free electricity.

Figure 1.2: Measuring height.

get light and heat but also mechanical energy that drives fans and electric motors etc. Consider the means of transportation such as car and aeroplanes; domestic appliances such as air-conditioners, refrigerators, vacuum-cleaners, washing machines, and microwave ovens etc. Similarly the means of communication such as radio, TV, telephone and computer are the result of applications of Physics. These devices have made our lives much easier, faster and more comfortable than the past. For example, think of what a mobile phone smaller than our palm can do? It allows us to contact people anywhere in the world and to get latest worldwide information. We can take and save pictures, send and receive messages of our friends. We can also receive radio transmission and can use it as a calculator as well.

However, the scientific inventions have also caused harms and destruction of serious nature. One of which is the environmental pollution and the other is the deadly weapons.

QUICK QUIZ

1. Why do we study physics?
2. Name any five branches of physics.

1.2 PHYSICAL QUANTITIES

All measurable quantities are called **physical quantities** such as length, mass, time and temperature. A physical quantity possesses at least two characteristics in common. One is its numerical magnitude and the other is the unit in which it is measured. For example, if the length of a student is 104 cm then 104 is its numerical magnitude and centimetre is the unit of measurement. Similarly when a grocer says that each bag contains 5 kg sugar, he is describing its numerical magnitude as well as the unit of measurement. It would be meaningless to state 5 or kg only. Physical quantities are divided into **base quantities** and **derived quantities.**

BASE QUANTITIES

There are seven physical quantities which form the foundation for other physical quantities. These physical quantities are called the base quantities. These are length, mass, time, electric current, temperature, intensity of light and the amount of a substance.

Base quantities are the quantities on the basis of which other quantities are expressed.

DERIVED QUANTITIES

Those physical quantities which are expressed in terms of base quantities are called the derived quantities. These include area, volume, speed, force, work, energy, power, electric charge, electric potential, etc.

The quantities that are expressed in terms of base quantities are called derived quantities.

1.3 INTERNATIONAL SYSTEM OF UNITS

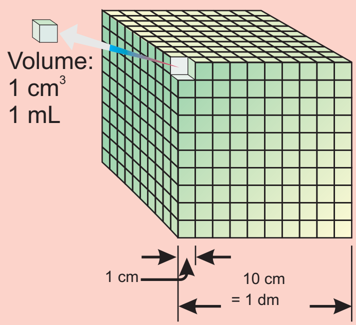
Measuring is not simply counting. For example, if we need milk or sugar, we must also understand how much quantity of milk or sugar we are talking about. Thus, there is a need of some standard quantities for measuring/comparing unknown quantities. Once a standard is set for a quantity then it can be expressed in terms of that standard quantity. This standard quantity is called a unit.

With the developments in the field of science and technology, the need for a commonly acceptable system of units was seriously felt all over the world particularly to exchange scientific and technical information. The eleventh General Conference on Weight and Measures held in Paris in 1960 adopted a world-wide system of measurements called **International System of Units.** The International System of Units is commonly referred as **SI.**

BASE UNITS

The units that describe base quantities are called base units. Each base quantity has its SI unit.

Mini Exercise



Volume is a derived quantity

$$1\,L = 1000\,mL$$
$$1\,L = 1\,dm^3$$
$$\therefore \quad = (10\,cm)^3$$
$$= 1000\,cm^3$$
$$\therefore \quad 1\,mL = 1\,cm^3$$

Express 1m^3 in litres L

Table 1.1 shows seven base quantities, their SI units and their symbols.

Table 1.1: Base quantities, their SI units with symbols

Quantity		Unit	
Name	**Symbol**	**Name**	**Symbol**
Length	*l*	metre	m
Mass	*m*	kilogramme	kg
Time	*t*	second	s
Electric current	*I*	ampere	A
Intensity of light	*L*	candela	cd
Temperature	*T*	kelvin	K
Amount of a substance	*n*	mole	mol

DERIVED UNITS

The units used to measure derived quantities are called derived units. Derived units are defined in terms of base units and are obtained by multiplying or dividing one or more base units with each other. The unit of area $(\text{metre})^2$ and the unit of volume $(\text{metre})^3$ are based on the unit of length, which is metre. Thus the unit of length is the base unit while the unit of area and volume are derived units. Speed is defined as distance covered in unit time; therefore its unit is metre per second. In the same way the unit of density, force, pressure, power etc. can be derived using one or more base units. Some derived units and their symbols are given in the Table 1.2.

Table 1.2: Derived quantities and their SI units with symbols

Quantity		Unit	
Name	**Symbol**	**Name**	**Symbol**
Speed	v	metre per second	ms^{-1}
Acceleration	a	metre per second per second	ms^{-2}
Volume	V	cubic metre	m^3
Force	F	newton	N or (kg m s^{-2})
Pressure	P	pascal	Pa or (N m^{-2})
Density	ρ	kilogramme per cubic metre	kg m^{-3}
Charge	Q	coulomb	C or (As)

QUICK QUIZ

1. How can you differentiate between base and derived quantities?
2. Identify the base quantity in the following:
   (i) Speed (ii) Area (iii) Force (iv) Distance
3. Identify the following as base or derived quantity: density, force, mass, speed, time, length, temperature and volume.

1.4 PREFIXES

Some of the quantities are either very large or very small. For example, 250 000 m, 0.002 W and 0.000 002 g, etc. SI units have the advantage that their multiples and sub-multiples can be expressed in terms of prefixes. Prefixes are the words or letters added before SI units such as kilo, mega, giga and milli. These prefixes are given in Table 1.3. The prefixes are useful to express very large or small quantities. For example, divide 20,000 g by 1000 to express it into kilogramme, since kilo represents 10^3 or 1000.

Table 1.3: Some Prefixes

Prefix	Symbol	Multiplier
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
deca	da	10^{1}
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}

Thus $$20{,}000\text{ g} = \frac{20{,}000}{1000}\text{ kg} = 20\text{ kg}$$

or $$20{,}000\text{ g} = 20\times10^{3}\text{ g} = 20\text{ kg}$$

Table 1.4 shows some multiples and sub-multiples of length. However, double prefixes are not used. For example, no prefix is used with kilogramme since it already contains the prefix kilo. Prefixes given in Table 1.3 are used with both types base and derived units. Let us consider few more examples:

(I) $200\,000\text{ ms}^{-1} = 200\times10^{3}\text{ ms}^{-1} = 200\text{kms}^{-1}$

(ii) $4\,800\,000\text{ W} = 4\,800\times10^{3}\text{W} = 4\,800\text{ kW}$

$= 4.8\times10^{6}\text{W} = 4.8\text{ MW}$

(iii) $3\,300\,000\,000\text{ Hz} = 3\,300\times10^{6}\text{ Hz} = 3300\text{ MHz}$

Table 1.4: Multiples and sub-multiples of length

1 km	10^{3} m
1 cm	10^{-2} m
1 mm	10^{-3} m
1 μm	10^{-6} m
1 nm	10^{-9} m

$= 3.3\text{x}10^{3}$ MHZ $= 3.3$ Ghz

(iv) 0.00002 g $= 0.02\text{x}10^{-3}$g $= 20\text{x}10^{-6}$g

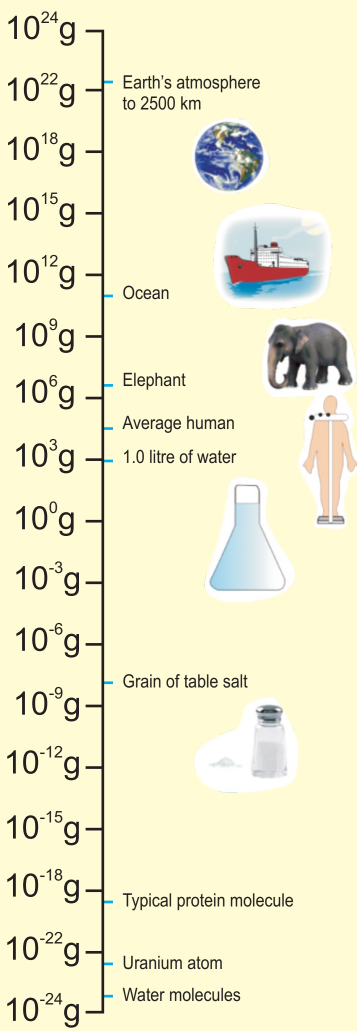
$= 20$ ug

(v) 0.000 000 0081m $= 0.0081\text{ x}10^{-6}$m $= 8.1\text{x}10^{-9}$m

$= 8.1$ nm

Tidbits

Mass of various objects



1.5 SCIENTIFIC NOTATION

A simple but scientific way to write large or small numbers is to express them in some power of ten. The Moon is 384000000 metres away from the Earth. Distance of the moon from the Earth can also be expressed as $3.84\text{ x}10^{8}$ m. This form of expressing a number is called the standard form or scientific notation. This saves writing down or interpreting large numbers of zeros. Thus

In scientific notation a number is expressed as some power of ten multiplied by a number between 1 and 10.

For example, a number **62750** can be expressed as $\mathbf{62.75\text{x}10^{3}}$ or $\mathbf{6.275\text{x}10^{4}}$ or $\mathbf{0.6275\text{x}10^{5}}$. All these are correct. But the number that has one non-zero digit before the decimal i.e. $\mathbf{6.275\text{x}10^{4}}$ preferably be taken as the standard form. Similarly the standard form of **0.00045 s** is $\mathbf{4.5\text{x}10^{-4}}$**s**.

1. Name five prefixes most commonly used.
2. The Sun is one hundred and fifty million kilometres away from the Earth. Write this
   (a) as an ordinary whole number.
   (b) in scientific notation.
3. Write the numbers given below in scientific notation.
   (a) 3000000000 ms^{-1} (b) 6400000 m
   (c) 0.0000000016 g (d) 0.0000548 s

1.6 MEASURING INSTRUMENTS

Measuring instruments are used to measure various physical quantities such as length, mass, time, volume, etc. Measuring instruments used in the past were not so reliable and accurate as we use today. For example, sundial, water clock and other time measuring devices used around 1300 AD were quite crude. On the other hand, digital clocks and watches used now-a-days are highly reliable and accurate. Here we shall describe some measuring instruments used in Physics laboratory.

FOR YOUR INFORMATION

Hubble Space Telescope orbits around the Earth. It provides information about stars.

THE METRE RULE

Figure 1.3: A metre rule

A metre rule is a length measuring instrument as shown in figure 1.3. It is commonly used in the laboratories to measure length of an object or distance between two points. It is one metre long which is equal to 100 centimetres. Each centimetre (cm) is divided into 10 small divisions called millimetre (mm). Thus one millimetre is the smallest reading that can be taken using a metre rule and is called its least count.

While measuring length, or distance, eye must be kept vertically above the reading point as shown in figure 1.4(b). The reading becomes doubtful if the eye is positioned either left or right to the reading point.

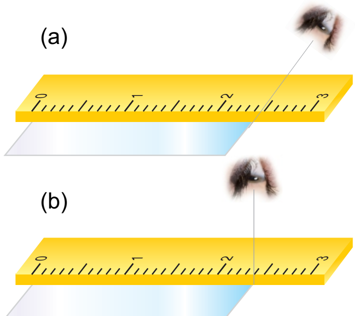


Figure 1.4: Wrong position of the eye to note the reading.
(b) Correct position of the eye to note the reading from a metre rule.

THE MEASURING TAPE

Measuring tapes are used to measure length in metres and centimetres. Figure 1.5 shows a measuring tape used by blacksmith and carpenters. A measuring tape consists of a thin and long strip of cotton, metal or plastic generally 10 m, 20 m, 50 m or 100 m long. Measuring tapes are marked in centimetres as well as in inches.

Figure 1.5: A measuring tape

VERNIER CALLIPERS

The accuracy obtained in measurements using a metre rule is upto 1 mm. However an accuracy greater than 1 mm can be obtained by using some

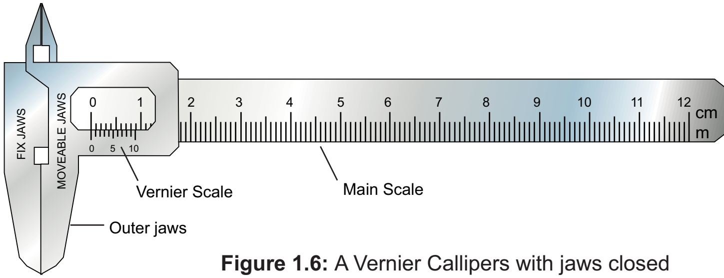


Figure 1.6: A Vernier Callipers with jaws closed

other instruments such as a Vernier Callipers. A Vernier Callipers consists of two jaws as shown in figure 1.6. One is a fixed jaw with main scale attached to it. Main scale has centimetre and millimetre marks on it. The other jaw is a moveable jaw. It has vernier scale having 10 divisions over it such that each of its division is 0.9 mm. The difference between one small division on main scale division and one vernier scale division is 0.1 mm. It is called least count (LC) of the Vernier Callipers. Least count of the Vernier Callipers can also be found as given below:

$$\text{Least count of Vernier Callipers} = \frac{\text{smallest reading on main scale}}{\text{no. of divisions on vernier scale}}$$

$$= \frac{1\,\text{mm}}{10\text{ divisions}} = 0.1\text{ mm}$$

Hence $\quad LC = 0.1\text{ mm} = 0.01\text{ cm}$

Mini Exercise

Cut a strip of paper sheet. Fold it along its length. Now mark centimetres and half centimetre along its length using a ruler. Answer the following questions:

1. What is the range of your paper scale?
2. What is its least count?
3. Measure the length of a pencil using your paper scale and with a metre ruler. Which one is more accurate and why?

Working of a Vernier Callipers

First of all find the error, if any, in the measuring instrument. It is called the zero error of the instrument. Knowing the zero error, necessary correction can be made to find the correct measurement. Such a correction is called zero correction of the instrument. Zero correction is the negative of zero error.

Zero Error and Zero Correction

To find the zero error, close the jaws of Vernier Callipers gently. If zero line of the vernier scale coincides with the zero of the main scale then the zero error is zero (figure 1.7a). Zero error will exist if zero line of the vernier scale is not coinciding with the zero of main scale (figure 1.7b). Zero error will be positive if zero line of vernier scale is on the right side of the zero of the main scale and will be negative if zero line of vernier scale is on the left side of zero of the main scale (figure 1.7c).

Taking a Reading on Vernier Callipers

Let us find the diameter of a solid cylinder using Vernier Callipers. Place the solid cylinder between jaws of the Vernier Callipers as shown in figure 1.8. Close the jaws till they press the opposite sides of the object gently.

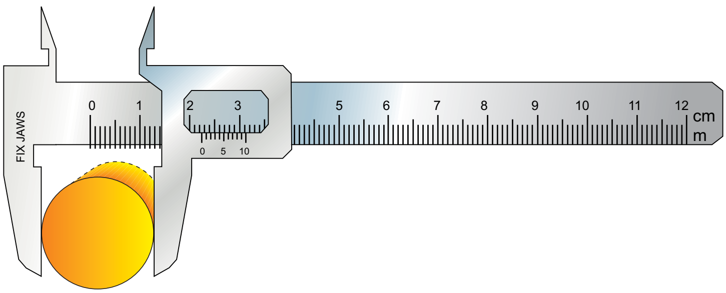


Figure 1.8: A cylinder placed between the outer jaws of Vernier Callipers.

Note the complete divisions of main scale past the vernier scale zero in a tabular form. Next find thevernier scale division that is coinciding with any division on the main scale. Multiply it by least count of Vernier Callipers and add it in the main scale reading. This is equal to the diameter of the solid cylinder. Add zero correction (Z.C) to get correct measurement. Repeat the above procedure and record at least three observations with the solid cylinder displaced or rotated each time.

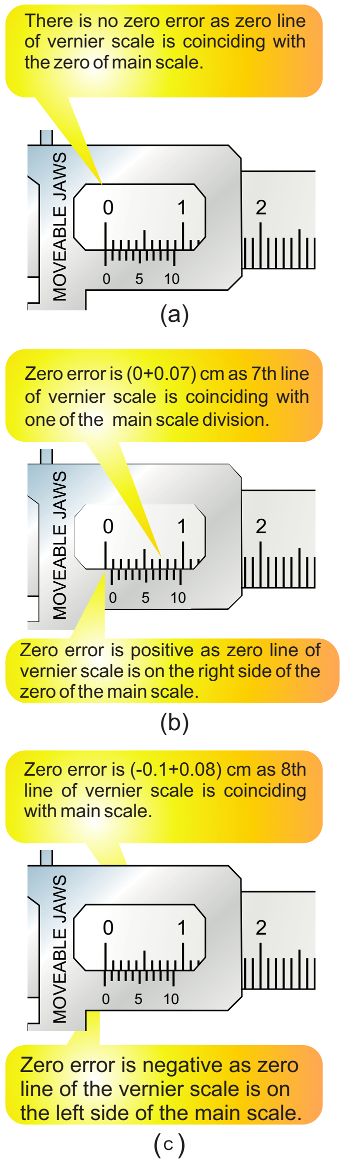


Figure 1.7: Zero Error
(a) zero
(b) +0.07 cm
© cm. -0.02

DIGITAL VERNIER CALLIPERS

Digital Vernier Callipers has greater precision than mechanical Vernier Callipers. Least count of Digital Vernier Callipers is 0.01 mm.

QUICK QUIZ

1. What is the least count of the Vernier Callipers?
2. What is the range of the Vernier Callipers used in your Physics laboratory?
3. How many divisions are there on its vernier scale?
4. Why do we use zero correction?

EXAMPLE 1.1

Find the diameter of a cylinder placed between the outer jaws of Vernier Callipers as shown in figure 1.8.

SOLUTION

Zero correction

On closing the jaws of Vernier Callipers, the position of vernier scale as shown in figure 1.7(b).

Main scale reading	= 0.0 cm
Vernier division coinciding with main scale	= 7 div.
Vernier scale reading	= 7 x 0.01 cm
	= 0.07 cm
Zero error	=0.0 cm+0.07 cm
	= +0.07 cm
zero correction (Z.C)	= - 0.07 cm

Diameter of the cylinder

Main scale reading	= 2.2 cm

(when the given cylinder is kept between the jaws of the Vernier Callipers as shown in figure 1.8).

Vernier div. coinciding with main scale div.	= 6 div.
Vernier scale reading	= 6 x 0.01 cm
	= 0.06 cm
Observed diameter of the cylinder	= 2.2 cm+0.06 cm
	= 2.26 cm
Correct diameter of the cylinder	= 2.26cm–0.07 cm
	= 2.19 cm

Thus, the correct diameter of the given cylinder as found by Vernier Callipers is 2.19 cm.

SCREW GAUGE

A screw gauge is an instrument that is used to measure small lengths with accuracy greater than a Vernier Calliper. It is also called as micrometer screw gauge. A simple screw gauge consists of a U-shaped metal frame with a metal stud at its one end as shown in figure 1.9. A hollow cylinder (or sleeve) has a millimetre scale over it along a line called index line parallel to its axis. The hollow cylinder acts as a nut. It is fixed at the end of U-shaped frame opposite to the stud. A Thimble has a threaded spindle inside it. As the thimble completes one rotation, the spindle moves 1 mm along the index line. It is because the distance between consecutive threads on the spindle is 1 mm. This distance is called the pitch of screw on the spindle.

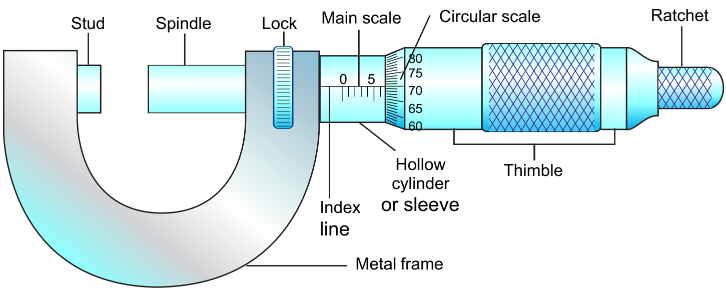
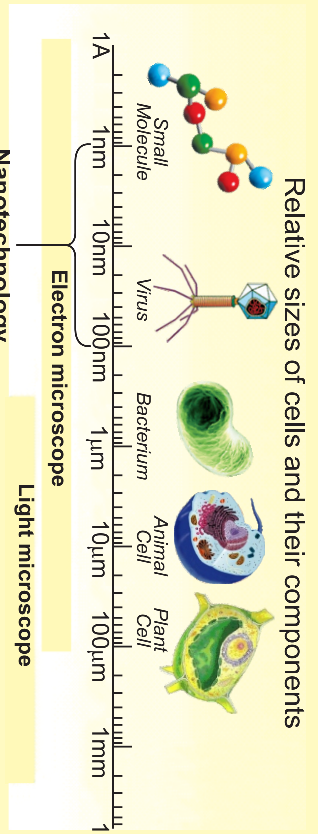


Figure 1.9: A micrometer screw gauge

Tidbits

Relative sizes of molecules and micro-organisms



The thimble has 100 divisions around its one end. It is the circular scale of the screw gauge. As thimble completes one rotation, 100 divisions pass the index line and the thimble moves 1 mm along the main scale. Thus each division of circular scale crossing the index line moves the thimble through 1/100 mm or 0.01 mm on the main scale. Least count of a screw gauge can also be found as given below:

$$\text{Least count} = \frac{\text{pitch of the screw gauge}}{\text{no. of divisions on circular scale}}$$

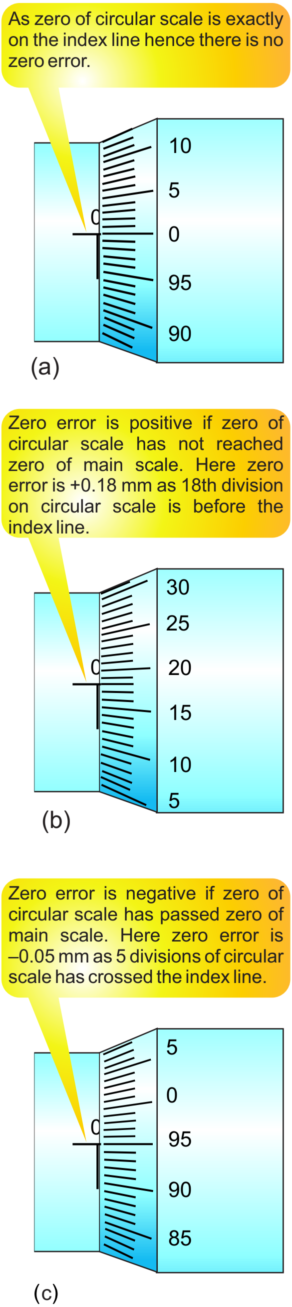


Figure 1.10: Zero Error in a screw gauge: (a) zero (b) + 0.18 mm (c) -0.05 mm.

$$= \frac{1\,\text{mm}}{100}$$

$$= 0.01\ \text{mm} = 0.001\ \text{cm}$$

Thus least count of the screw gauge is 0.01 mm or 0.001 cm.

WORKING OF A SCREW GAUGE

The first step is to find the zero error of the screw gauge.

ZERO ERROR

To find the zero error, close the gap between the spindle and the stud of the screw gauge by rotating the ratchet in the clockwise direction. If zero of circular scale coincides with the index line, then the zero error will be zero as shown in figure 1.10(a).

Zero error will be positive if zero of circular scale is behind the index line. In this case, multiply the number of divisions of the circular scale that has not crossed the index line with the least count of screw gauge to find zero error as shown in figure 1.10(b).

Zero error will be negative if zero of circular scale has crossed the index line. In this case, multiply the number of divisions of the circular scale that has crossed the index line with the least count of screw gauge to find the negative zero error as shown in figure 1.10(c).

EXAMPLE 1.2

Find the diameter of a wire using a screw gauge.

SOLUTION

The diameter of a given wire can be found as follows:

(i) Close the gap between the spindle and the stud of the screw gauge by turning the ratchet in the clockwise direction.

(ii) Note main scale as well as circular scale readings to find zero error and hence zero correction of the screw gauge.

(iii) Open the gap between stud and spindle of the screw gauge by turning the ratchet in anti clockwise direction. Place the given wire in the gap as shown in figure 1.11. Turn the ratchet so that the object is pressed gently between the studs and the spindle.

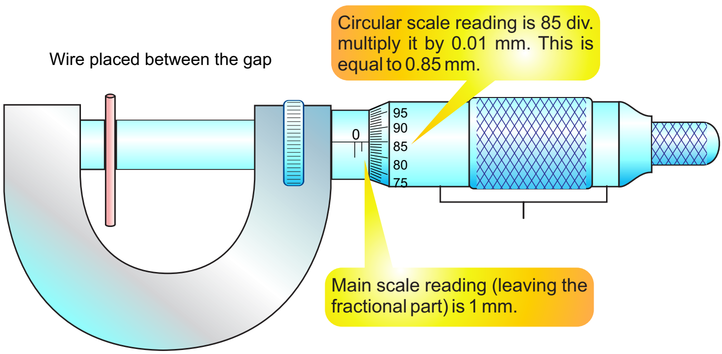


Figure 1.11: Measuring the diameter of a wire using micrometer screen gauge.

(iv) Note main scale as well as circular scale readings to find the diameter of the given wire.

(v) Apply zero correction to get the correct diameter of the wire.

(vi) Repeat steps iii, iv and v at different places of the wire to obtain its average diameter.

Zero correction

Closing the gap of the screw gauge (figure 1.12).

Main scale reading = 0 mm

Circular scale reading = 24 x 0.01 mm

Zero error of the screw gauge = 0 mm+0.24 mm

= + 0.24 mm

Zero correction Z.C. = -0.24 mm

Diameter of the wire (figure 1.11)

Main scale reading = 1 mm

(when the given wire is pressed by the stud and spindle of the screw gauge)

Mini Exercise

1. What is the least count of a screw gauge?
2. What is the pitch of your laboratory screw gauge?
3. What is the range of your laboratory screw gauge?
4. Which one of the two instruments is more precise and why?

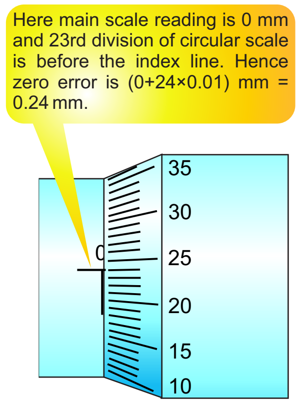


Figure 1.12: Zero error of the screw gauge

USEFUL INFORMATION

Least count of ruler is 1 mm. It is 0.1 mm for Vernier Callipers and 0.01mm for micrometer screw gauge. Thus measurements taken by micrometer screw gauge are the most precise than the other two.

No. of divisions on circular scale	= 85 div.
Circular scale reading	= 85x0.01 mm
	= 0.85 mm
Observed diameter of the given wire	=1mm+0.85 mm
	= 1.85 mm
Correct diameter of the given wire	= 1.85 mm - 0.24 mm
	= 1.61 mm

Thus diameter of the given wire is 1.61 mm.

MASS MEASURING INSTRUMENTS

Pots were used to measure grain in various part of the world in the ancient times. However, balances were also in use by Greeks and Romans. Beam balances such as shown in figure 1.13 are still in use at many places. In a beam balance, the unknown mass is placed in one pan. It is balanced by putting known masses in the other pan. Today people use many types of mechanical and electronic balances. You might have seen electronic balances in sweet and grocery shops. These are more precise than beam balances and are easy to handle.

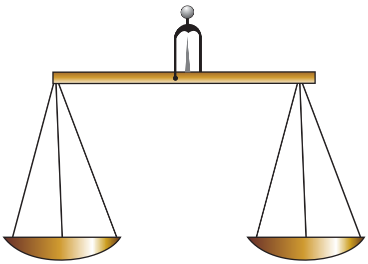


Figure 1.13: A beam balance

PHYSICAL BALANCE

A physical balance is used in the laboratory to measure the mass of various objects by comparison. It consists of a beam resting at the centre on a fulcrum

Mini Exercise

1. What is the function of balancing screws in a physical balance?
2. On what pan we place the object and why?

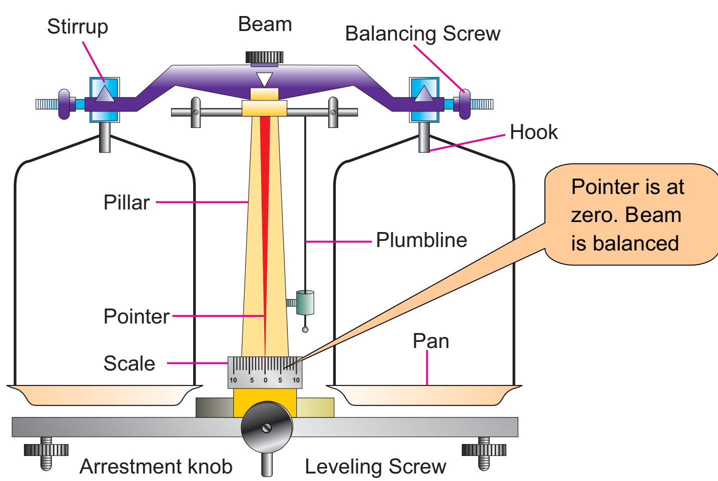


Figure 1.14: A physical balance

as shown in the figure 1.14. The beam carries scale pans over the hooks on either side. Unknown mass is placed on the left pan. Find some suitable standard masses that cause the pointer to remain at zero on raising the beam.

as shown in the figure 1.14. The beam carries scale pans over the hooks on either side. Unknown mass is placed on the left pan. Find some suitable standard masses that cause the pointer to remain at zero on raising the beam.

EXAMPLE 1.3

Find the mass of a small stone by a physical balance.

SOLUTION

Follow the steps to measure the mass of a given object.

(i) Adjusting the levelling screws with the help of plumbline to level the platform of physical balance.

(ii) Raise the beam gently by turning the arresting knob clockwise. Using balancing screws at the ends of its beam, bring the pointer at zero position.

(iii) Turn the arresting knob to bring the beam back on its supports. Place the given object (stone) on its left pan.

(iv) Place suitable standard masses from the weight box on the right pan. Raise the beam. Lower the beam if its pointer is not at zero.

(v) Repeat adding or removing suitable standard masses in the right pan till the pointer rests at zero on raising the beam.

(vi) Note the standard masses on the right pan. Their sum is the mass of the object on the left pan.

LABORATORY SAFETY EQUIPMENT

Fire extinguisher

LEVER BALANCE

A lever balance such as shown in figure 1.15 consists of a system of levers. When lever is lifted placing the object in one pan and standard masses on the other pan, the pointer of the lever system moves. The pointer is brought to zero by varying standard masses.

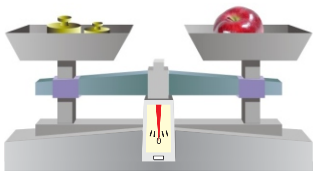


Figure 1.15: A lever balance

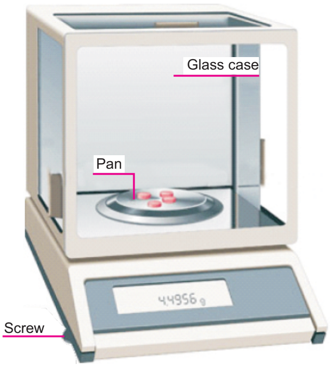


Figure 1.16: An electronic balance

USEFUL INFORMATION

The precision of a balance in measuring mass of an object is different for different balances. A sensitive balance cannot measure large masses. Similarly, a balance that measures large masses cannot be sensitive.

Some digital balances measure even smaller difference of the order of 0.0001g or 0.1 mg. Such balances are considered the most precise balance.

Figure 1.17: A mechanical stopwatch

ELECTRONIC BALANCE

Electronic balances such as shown in figure 1.16 come in various ranges; milligram ranges, gram ranges and kilogramme ranges. Before measuring the mass of a body, it is **switched ON** and its reading is **set to zero**. Next place the object to be weighed. The reading on the balance gives you the mass of the body placed over it.

The most Accurate Balance

The mass of one rupee coin is done using different balances as given below:

(a) Beam Balance

Let the balance measures coin's mass = 3.2 g

A sensitive beam balance may be able to detect a change as small as of 0.1 g Or 100 mg.

(b) Physical Balance

Let the balance measures coin's mass = 3.24 g

Least count of the physical balance may be as small as 0.01 g or 10 mg. Therefore, its measurement would be more precise than a sensitive beam balance.

(c) Electronic Balance

Let the balance measures coin's mass = 3.247 g

Least count of an electronic balance is 0.001 g or 1 mg. Therefore, its measurement would be more precise than a sensitive physical balance. Thus electronic balance is the most sensitive balance in the above balances.

STOPWATCH

A stopwatch is used to measure the time interval of an event. There are two types of stopwatches; mechanical and digital as shown in figure 1.17 and 1.18. A mechanical stopwatch can measure a time interval up to a minimum 0.1 second. Digital stopwatches commonly used in laboratories can measure a time interval as small as 1/100 second or 0.01 second.

How to use a Stopwatch

A mechanical stopwatch has a knob that is used to wind the spring that powers the watch. It can also be used as a start-stop and reset button. The watch starts when the knob is pressed once. When pressed second time, it stops the watch while the third press brings the needle back to zero position.

The digital stopwatch starts to indicate the time lapsed as the start/stop button is pressed. As soon as start/stop button is pressed again, it stops and indicates the time interval recorded by it between start and stop of an event. A reset button restores its initial zero setting.

MEASURING CYLINDER

A measuring cylinder is a glass or transparent plastic cylinder. It has a scale along its length that indicates the volume in millilitre (mL) as shown in figure 1.19. Measuring cylinders have different capacities from 100 mL to 2500 mL. They are used to measure the volume of a liquid or powdered substance. It is also used to find the volume of an irregular shaped solid insoluble in a liquid by displacement method. The solid is lowered into a measuring cylinder containing water/liquid. The level of water/liquid rises. The increase in the volume of water/liquid is the volume of the given solid object.

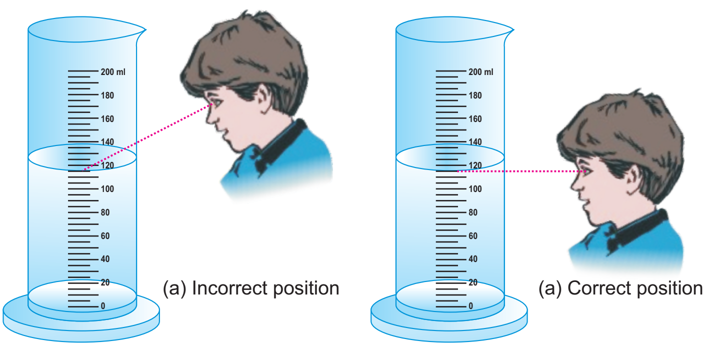


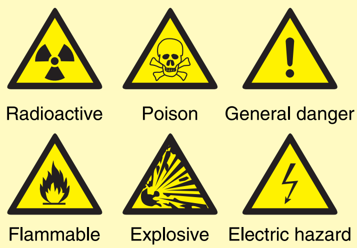
Figure 1.19(**a**) Wrong way to note the liquid level keeping eye above liquid level, (b) correct position of eye to note the liquid level keeping eye at liquid level.

Figure 1.18: A digital stopwatch

LABORATORY SAFETY EQUIPMENTS

A school laboratory must have safety equipments such as:

- Waste-disposal basket
- Fire extinguisher.
- Fire alarm.
- First Aid Box.
- Sand and water buckets.
- Fire blanket to put off fire.
- Substances and equipments that need extra care must bear proper warning signs such as given below:



LABORATORY SAFETY RULES

The students should know what to do in case of an accident. The charts or posters are to be displayed in the laboratory to handle situations arising from any mishap or accident. For your own safety and for the safety of others in the laboratory, follow safety rules given below:

- Do not carry out any experiment without the permission of your teacher.
- Do not eat, drink, play or run in the laboratory.
- Read the instructions carefully to familiarize yourself with the possible hazards before handling equipments and materials.
- Handle equipments and materials with care.
- Do not hesitate to consult your teacher in case of any doubt.
- Do not temper with the electrical appliances and other fittings in the laboratory.
- Report any accident or injuries immediately to your teacher.

HOW TO USE A MEASURING CYLINDER

While using a measuring cylinder, it must be kept vertical on a plane surface. Take a measuring cylinder. Place it vertically on the table. Pour some water into it. Note that the surface of water is curved as shown in figure 1.19. The meniscus of the most liquids curve downwards while the meniscus of mercury curves upwards. The correct method to note the level of a liquid in the cylinder is to keep the eye at the same level as the meniscus of the liquid as shown in figure 1.19(b). It is incorrect to note the liquid level keeping the eye above the level of liquid as shown in figure 1.19 (a). When the eye is above the liquid level, the meniscus appears higher on the scale. Similarly when the eye is below the liquid level, the meniscus appears lower than actual height of the liquid.

MEASURING VOLUME OF AN IRREGULAR SHAPED SOLID

Measuring cylinder can be used to find the volume of a small irregular shaped solid that sinks in water. Let us find the volume of a small stone. Take some water in a graduated measuring cylinder. Note the volume V_i of water in the cylinder. Tie the solid with a thread. Lower the solid into the cylinder till it is fully immersed in water. Note the volume V_f of water and the solid. Volume of the solid will be $V_f - V_i$.

1.7 SIGNIFICANT FIGURES

The value of a physical quantity is expressed by a number followed by some suitable unit. Every measurement of a quantity is an attempt to find its true value. The accuracy in measuring a physical quantity depends upon various factors:

+ the quality of the measuring instrument
+ the skill of the observer
+ the number of observations made

For example, a student measures the length of a book as 18 cm using a measuring tape. The numbers of significant figures in his/her measured

value are two. The left digit 1 is the accurately known digit. While the digit 8 is the doubtful digit for which the student may not be sure.

Another student measures the same book using a ruler and claims its length to be 18.4 cm. In this case all the three figures are significant. The two left digits 1 and 8 are accurately known digits. Next digit 4 is the doubtful digit for which the student may not be sure.

A third student records the length of the book as 18.425 cm. Interestingly, the measurement is made using the same ruler. The numbers of significant figures is again three; consisting of two accurately known digits 1, 8 and the first doubtful digit 4. The digits 2 and 5 are not significant. It is because the reading of these last digits cannot be justified using a ruler. Measurement upto third or even second decimal place is beyond the limit of the measuring instrument.

An improvement in the quality of measurement by using better instrument increases the significant figures in the measured result. The significant figures are all the digits that are known accurately and the one estimated digit. More significant figure means greater precision. The following rules are helpful in identifying significant figure:

(i) Non-zero digits are always significant.

(ii) Zeros between two significant figures are also significant.

(iii) Final or ending zeros on the right in decimal fraction are significant.

(iv) Zeros written on the left side of the decimal point for the purpose of spacing the decimal point are not significant.

(v) In whole numbers that end in one or more zeros without a decimal point. These zeros may or may not be significant. In such cases, it is not clear which zeros serve to

RULES TO FIND THE SIGNIFICANT DIGITS IN A MEASUREMENT

(i) Digits other than zero are always significant.

27 has 2 significant digits.

275 has 3 significant digits.

(ii) Zeros between significant digits are also significant.

2705 has 4 significant digits.

(iii) Final zero or zeros after decimal are significant.

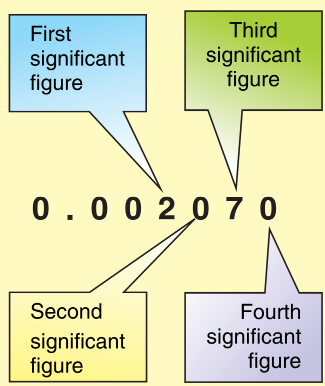
275.00 has 5 significant digits.

(iv) Zeros used for spacing the decimal point are not significant. Here zeros are placeholders only.

0.03 has 1 significant digit.

0.027 has 2 significant digits.

EXAMPLE



locate the position value and which are actually parts of the measurement. In such a case, express the quantity using scientific notation to find the significant zero.

EXAMPLE 1.4

Find the number of significant figures in each of the following values. Also express them in scientific notations.

a) 100.8 s b) 0.00580 km

c) 210.0 g

SOLUTION

(a) All the four digits are significant. The zeros between the two significant figures 1 and 8 are significant. To write the quantity in scientific notation, we move the decimal point two places to the left, thus

$100.8\ s = 1.008 \times 10^2\ s$

(b) The first two zeros are not significant. They are used to space the decimal point. The digit 5,8 and the final zero are significant. Thus there are three significant figures. In scientific notation, it can be written as 5.80×10^{-3} km.

(c) The final zero is significant since it comes after the decimal point. The zero between last zero and 1 is also significant because it comes between the significant figures. Thus the number of significant figures in this case is four. In scientific notation, it can be written as

$210.0\ g = 2.100 \times 10^2 g$

Rounding the Numbers

(i) If the last digit is less than 5 then it is simply dropped. This decreases the number of significant digits in the figure.

For example,

1.943 is rounded to 1.94 (3 significant figure)

(ii) If the last digit is greater than 5, then the digit on its left is increased by one. This also decreases the number of significant digits in the figure.

For example,

1.47 is rounded to two significant digits 1.5

(iii) If the last digit is 5, then it is rounded to get nearest even number.

For example,

1.35 is rounded to 1.4 and 1.45 is also rounded to 1.4

SUMMARY

- Physics is a branch of Science that deals with matter, energy and their relationship.
- Some main branches of Physics are mechanics, heat, sound, light (optics), electricity and magnetism, nuclear physics and quantum physics.
- Physics plays an important role in our daily life. For example, electricity is widely used everywhere, domestic appliances, office equipments, machines used in industry, means of transport and communication etc. work on the basic laws and principles of Physics.
- A measurable quantity is called a physical quantity.
- Base quantities are defined independently. Seven quantities are selected as base quantities. These are length, time, mass, electric current, temperature, intensity of light and the amount of a substance.
- The quantities which are expressed in terms of base quantities are called derived quantities. For example, speed, area, density, force, pressure, energy, etc.
- A world-wide system of measurements is known as international system of units (SI). In SI, the units of seven base quantities are metre, kilogramme, second, ampere, kelvin, candela and mole.
- The words or letters added before a unit and stand for the multiples orsub-multiples of that unit are known as prefixes. For example, kilo, mega, milli, micro, etc.
- A way to express a given number as a number between 1 and 10 multiplied by 10 having an appropriate power is called scientific notation or standard form.
- An instrument used to measure small lengths such as internal or external diameter or length of a cylinder, etc is called as Vernier Callipers.
- A Screw gauge is used to measure small lengths such as diameter of a wire, thickness of a metal sheet, etc.
- Physical balance is a modified type of beam balance used to measure small masses by comparison with greater accuracy.
- A stopwatch is used to measure the time interval of an event. Mechanical stopwatches have least count upto 0.1 seconds. Digital stopwatch of least count 0.01s are common.
- A measuring cylinder is a graduated glass cylinder marked in millilitres. It is used to measure the volume of a liquid and also to find the volume of an irregular shaped solid object.
- All the accurately known digits and the first doubtful digit in an expression are called significant figures. It reflects the precision of a measured value of a physical quantity.

QUESTIONS

1.1 Encircle the correct answer from the given choices.

i. The number of base units in SI are:

(a) 3 (b)6 (c)7 (d)9

ii. Which one of the following unit is not a derived unit?

(a) pascal (b) kilogramme

(c) newton (d) watt

iii. Amount of a substance in terms of numbers is measured in:

(a) gram (b) kilogramme

(c) newton (d) mole

iv. An interval of 200u s is equivalent to

(a) 0.2 s (b) 0.02 s

(c) $2x10^{-4}$s (d) $2x10^{-6}$s

v. Which one of the following is the smallest quantity?

(a) 0.01 g (b) 2 mg

(c) 100 u g (d) 5000 ng

vi. Which instrument is most suitable to measure the internal diameter of a test tube?

(a) metre rule

(b) Vernier Callipers

(c) measuring tap

(d) screw gauge

vii. A student claimed the diameter of a wire as 1.032 cm using Vernier Callipers. Upto what extent do you agree with it?

(a) 1 cm (b) 1.0 cm

(c) 1.03 cm (d) 1.032 cm

viii. A measuring cylinder is used to measure:

(a) mass (b) area

(c) volume (d) level of a liquid

ix. A student noted the thickness of a glass sheet using a screw gauge. On the main scale, it reads 3 divisions while 8th division on the circular scale coincides with index line. Its thickness is:

(a) 3.8 cm (b) 3.08 mm

(c) 3.8 mm (d) 3.08 m

x. Significant figures in an expression are :

(a) all the digits

(b) all the accurately known digits

(c) all the accurately known digits and the first doubtful digit

(d) all the accurately known and all the doubtful digits

1.2 What is the difference between base quantities and derived quantities? Give three examples in each case.

1.3 Pick out the base units in the following:
joule, newton, kilogramme, hertz, mole, ampere, metre, kelvin, coulomb and watt.

1.4 Find the base quantities involved in each of the following derived quantities:

(a) speed (b) volume
(c) force (d) work

1.5 Estimate your age in seconds.

1.6 What role SI units have played in the development of science?

1.7 What is meant by vernier constant?

1.8 What do you understand by the zero error of a measuring instrument?

1.9 Why is the use of zero error necessary in a measuring instrument?

1.10 What is a stopwatch? What is the least count of a mechanical stopwatch you have used in the laboratories?

1.11 Why do we need to measure extremely small interval of times?

1.12 What is meant by significant figures of a measurement?

1.13 How is precision related to the significant figures in a measured quantity?

PROBLEMS

1.1 Express the following quantities using prefixes.

(a) 5000 g
(b) 2000 000 W
(b) 52 $\times 10^{-10}$ kg
(c) 225$\times 10^{-8}$s
{(a) 5 kg (b)2MW
(c) 5.2 ug (d) 2.25 us }

1.2 How do the prefixes micro, nano and pico relate to each other?

1.3 Your hair grow at the rate of 1 mm per day. Find their growth rate in nm s^{-1}. (11.57 nm s^{-1})

1.4 Rewrite the following in standard form.

(a) 1168$\times 10^{-27}$ (b) 32$\times 10^{-5}$
(c) 725$\times 10^{-5}$ kg (d) 0.02 $\times 10^{-8}$
{(a) 1.168$\times 10^{-24}$ (b) 3.2$\times 10^{6}$
(c)7.25g (d) 2$\times 10^{-10}$}

1.5 Write the following quantities in standard form.

(a) 6400 km
(b) 380 000 km
(c) 300 000 000 ms^{-1}
(d) seconds in a day
{(a) 6.4$\times 10^{3}$ km (b) 3.8$\times 10^{5}$ km
(c) 3$\times 10^{8}$ms1 (d) 8.64$\times 10^{4}$s}

1.6 On closing the jaws of a Vernier Callipers, zero of the vernier scale is on the right to its main scale such that 4th division of its vernier scale coincides with one of the main scale division. Find its zero error and zero correction.

(+0.04 cm, -0.04 cm)

1.7 A screw gauge has 50 divisions on its circular scale. The pitch of the screw gauge is 0.5 mm. What is its least count?

(0.001 cm)

1.8 Which of the following quantities have three significant figures?

(a) 3.0066 m (b) 0.00309 kg

(c) 5.05×10^{-27} kg (d) 301.0 s

{(b) and (c)}

1.9 What are the significant figures in the following measurements?

(a) 1.009 m (b) 0.00450 kg

(c) 1.66×10^{-27} kg (d) 2001 s

{(a) 4 (b) 3 (c) 3 (d) 4}

1.10 A chocolate wrapper is 6.7 cm long and 5.4 cm wide. Calculate its area upto reasonable number of significant figures.

(36 cm2)

Unit 2

Kinematics

STUDENT'S LEARNING OUTCOMES

After studying this unit, the students will be able to:

- describe using examples how objects can be at rest and in motion simultaneously.
- identify different types of motion i.e. translator/, (linear, random, and circular); rotatory and vibratory motions and distinguish among them.
- differentiate with examples between distance and displacement, speed and velocity.
- differentiate with examples between scalar and vector quantities.
- represent vector quantities by drawing.
- define the terms speed, velocity and acceleration.
- plot and interpret distance-time graph and speed-time graph.
- determine and interpret the slope of distance-time and speed-time graph.
- determine from the shape of the graph, the state of a body
  - i. at rest
  - ii. moving with constant speed
  - iii. moving with variable speed.

This unit is built on
Force and Motion
- Science-IV

This unit leads to:
Motion and force
- Physics-X

Major Concepts

2.1 Rest and motion

2.2 Types of motion (Translator/, rotatory, vibratory)

2.3 Terms associated with motion;
- Position
- Distance and displacement
- Speed and velocity
- Acceleration

2.4 Scalars and vectors

2.5 Graphical analysis of motion;
- Distance-time graph
- Speed-timegraph

2.6 Equations of Motion;
- $S = vt$
- $v_f = v_i + at$
- $S = v_i t + \frac{1}{2} at^2$
- $v_f^2 - v_i^2 = 2aS$

2.7 Motion due to gravity

- calculate the area under speed-time graph to determine the distance travelled by the moving body.
- derive equations of motion for a body moving with uniform acceleration in a straight line using graph.
- solve problems related to uniformly accelerated motion using appropriate equations.
- solve problems related to freely falling bodies using 10 ms^{-2} as the acceleration due to gravity.

INVESTIGATION SKILLS:

The students will be able to:

- demonstrate various types of motion so as to distinguish between translatory, rotatory and vibratory motions.
- measure the average speed of a 100 m sprinter.

SCIENCE, TECHNOLOGY AND SOCIETY CONNECTION:

The students will be able to:

- list the effects of various means of transportation and their safety issues.
- the use of mathematical slopes (ramps) of graphs or straight lines in real life applications.
- interpret graph from newspaper, magazine regarding cricket and weather etc.

The first thing concerning the motion of an object is its kinematics. Kinematics is the study of motion of an object without discussing the cause of motion. In this unit, we will study the types of motion, scalar and vector quantities, the relation between displacement, speed, velocity and acceleration; linear motion and equations of motion.

2.1 REST AND MOTION

We see various things around us. Some of them are at rest while others are in motion.

A body is said to be at rest, if it does not change its position with respect to its surroundings.

Surroundings are the places in its neighbourhood where various objects are present. Similarly,

A body is said to be in motion, if it changes its position with respect to its surroundings.

Figure 2.1: The passengers in the bus are also moving with it.

The state of rest or motion of a body is relative. For example, a passenger sitting in a moving bus is at rest because he/she is not changing his/her position with respect to other passengers or objects in the bus. But to an observer outside the bus, the passengers and the objects inside the bus are in motion.

Figure 2.: A car and an aeroplane moving along a straight line are in linear motion.

2.2 TYPES OF MOTION

If we observe carefully, we will find that everything in the universe is in motion. However, different objects move differently. Some objects move along a straight line, some move in a curved path, and some move in some other way. There are three types of motion.

(I) Translatory motion (linear, random and circular)

(ii) Rotatory motion

(iii) Vibratory motion (to and fro motion)

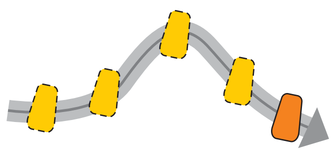


Figure 2.3: Translatory motion of an object along a curved path.

TRANSLATORY MOTION

Watch how various objects are moving. Do they move along a straight line? Do they move along a circle? A car moving in a straight line has translational motion. Similarly, an aeroplane moving straight is in translational motion.

In translational motion, a body moves along a line without any rotation. The line may be straight or curved.

Figure 2.4: Translatory motion of riders in Ferris wheel.

Figure 2.5: Linear motion of the ball falling down.

The object as shown in figure 2.3 moves along a curved path without rotation. This is the translational motion of the object. Riders moving in a Ferris wheel such as shown in figure 2.4 are also in translational motion. Their motion is in a circle without rotation. Translatory motions can be divided into linear motion, circular motion and random motion.

LINEAR MOTION

We come across many objects which are moving in a straight line. The motion of objects such as a car moving on a straight and level road is linear motion.

Straight line motion of a body is known as its linear motion.

Aeroplanes flying straight in air and objects falling vertically down are also the examples of linear motion.

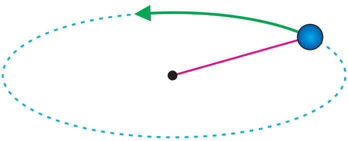


Figure 2.6: A stone tied at the end of a string moves in a circle.

CIRCULAR MOTION

A stone tied at the end of a string can be made to whirl. What type of path is followed by the stone? The stone as shown in figure 2.6, moves in a circle and thus has circular motion.

The motion of an object in a circular path is known as circular motion.

Figure 2.7: A toy train moving on a circular track.

Figure 2.7 shows a toy train moving on a circular track. A bicycle or a car moving along a circular track possesses circular motion. Motion of the Earth around the Sun and motion of the moon around the Earth are also the examples of circular motions.

RANDOM MOTION

Have you noticed the type of motion of insects and birds? Their movements are irregular.

The disordered or irregular motion of an object is called random motion.

Thus, motion of insects and birds is random motion. The motion of dust or smoke particles in the air is also random motion. The Brownian motion of a gas or liquid molecules along a zig-zag path such as shown in figure 2.8 is also an example of random motion.

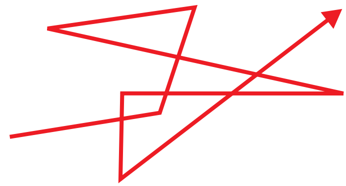


Figure 2.8: Random motion of gas molecules is called Brownian motion.

ROTATORY MOTION

Study the motion of a top. It is spinning about an axis. Particles of the spinning top move in circles and thus individual particles possess circular motion. Does the top possess circular motion?

The top shown in figure 2.9 spins about its **axis** passing through it and thus it possesses rotatory motion. An **axis** is a line around which a body rotates. In circular motion, the point about which a body goes around, is outside the body. In rotatory motion, the line, around which a body moves about, is passing through the body itself.

Can you spin a ball at the tip of the finger?

The spinning motion of a body about its axis is called its rotatory motion.

Can you point out some more differences in circular and rotatory motion?

The motion of a wheel about its axis and that of a steering wheel are the examples of rotatory motion. The motion of the Earth around the Sun is circular motion and not the spinning motion. However, the motion of the Earth about its geographic axis that causes day and night is rotatory motion. Think of some more examples of rotatory motion.

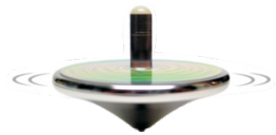


Figure 2.9: Rotatory motion

Figure2.10: Vibratory motion of a child and a swing..

Figure2.11: Vibratory motion of the pendulum of a clock.

VIBRATORY MOTION

Consider a baby in a swing as shown in figure 2.10. As it is pushed, the swing moves back and forth about its mean position. The motion of the baby repeats from one extreme to the other extreme with the swing.

To and fro motion of a body about its mean position is known as vibratory motion.

Figure 2.11 shows to and fro motion of the pendulum of a clock about its mean position, it is called vibratory motion. We can find many examples of vibratory motion around us. Look at the children in a see-saw as shown in figure 2.12. How the children move as they play the see-saw game? Do they possess vibratory motion as they move the see-saw?

Figure 2.12: Vibratory motion of children in a see-saw.

A baby in a cradle moving to and fro, to and fro motion of the hammer of a ringing electric bell and the motion of the string of a sitar are some of the examples of vibratory motion.

Mini Exercise

1. When a body is said to be at rest?
2. Give an example of a body that is at rest and is in motion at the same time.
3. Mention the type of motion in each of the following:

(i) A ball moving vertically upward.

(ii) A child moving down a slide.

(iii) Movement of a player in a football ground.

(iv) The flight of a butterfly.

(v) An athlete running in a circular track.

(vi) The motion of a wheel.

(vii) The motion of a cradle.

2.3 SCALARS AND VECTORS

In Physics, we come across various quantities such as mass, length, volume, density, speed and force etc. We divide them into scalars and vectors.

SCALARS

A physical quantity which can be completely described by its magnitude is called a scalar. The magnitude of a quantity means its numerical value with an appropriate unit such as 2.5 kg, 40 s, 1.8 m, etc. Examples of scalars are mass, length, time, speed, volume, work and energy.

A scalar quantity is described completely by its magnitude only.

VECTORS

A vector can be described completely by magnitude alongwith its direction. Examples of vectors are velocity, displacement, force, momentum, torque, etc. It would be meaningless to describe vectors without direction. For example, distance of a place from reference point is insufficient to locate that place. The direction of that place from reference point is also necessary to locate it.

A vector quantity is described completely by magnitude and direction.

Consider a table as shown in figure 2.13 (a). Two forces F_1 and F_2 are acting on it. Does it make any difference if the two forces act in opposite direction such as indicated in figure 2.13(b)?

Certainly the two situations differ from each other. They differ due to the direction of the forces acting on the table. Thus the description of a force would be incomplete if direction is not given. Similarly when we say, we are walking at the rate of 3 kmh^{-1} towards north then we are talking about a vector.

(a)

(b)

Figure 2.13: Two forces F_1 and F_2 (a) both acting in the same direction. (b) acting in opposite directions.

To differentiate a vector from a scalar quantity, we generally use bold letters to represent vector quantities, such as **F, a, d** or a bar or arrow over theirsymbols such as $\overline{F}$, $\overline{a}$, $\overline{d}$ or $\vec{F}$, $\vec{a}$ and $\vec{d}$.

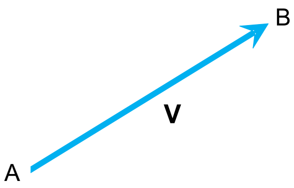


Figure 2.14: Graphical representation of a vector **V**

Graphically, a vector can be represented by a line segment with an arrow head. In figure 2.14, the line AB with arrow head at B represents a vector **V**. The length of the line AB gives the magnitude of the vector **V** on a selected scale. While the direction of the line from A to B gives the direction of the vector **V**.

EXAMPLE 2.1

Represent a force of 80 N acting toward North of East.

SOLUTION

Stepl: Draw two lines perpendicular to each other. Horizontal line represents East-West and vertical line represents North-South direction as shown in figure 2.15.

Step2: Select a suitable scale to represent the given vector. In this case we may take a scale which represents 20 N by 1 cm line.

Step3: Draw a line according to the scale in the direction of the vector. In this case, draw a line OA of length 4 cm along North-East.

Step4: Put an arrow head at the end of the line. In this case arrow head is at point A. Thus, the line OA will represent a vector i.e., the force of 80 N acting towards North-East.

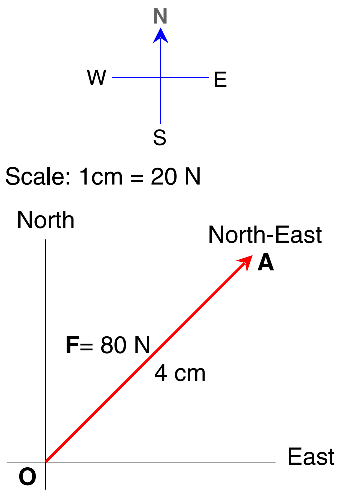


Figure 2.15: Representing 80 N force acting North-East.

2.4 TERMS ASSOCIATED WITH MOTION

When dealing with motion, we come across various terms such as the position of an object; the distance covered by it, its speed and so on. Let us explain some of the terms used.

POSITION

The term position describes the location of a place or a point with respect to some reference point called origin. For example, you want to describe the position of your school from your home. Let the school be represented by S and home by H. The position of your school from your home will be represented by a straight line HS in the direction from H to S as shown in figure 2.16.

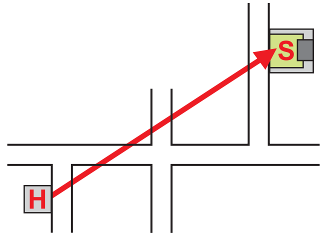


Figure 2.16: Position of the school S from the home H.

DISTANCE AND DISPLACEMENT

Figure 2.17 shows a curved path. Let *S* be the length of the curved path between two points A and B on it. Then S is the distance between points A and B.

Length of a path between two points is called the distance between those points.

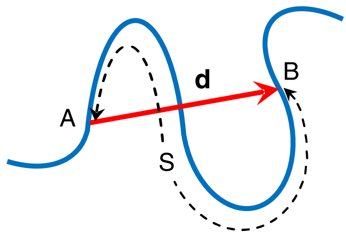


Figure 2.17: Distance S (dotted line) and displacement **d** (red line) from points A to B.

Consider a body that moves from point A to point B along the curved path. Join points A and B by a straight line. The straight line AB gives the distance which is the shortest between A and B. This shortest distance has magnitude d and direction from point A to B. This shortest distance d in a particular direction is called displacement. It is a vector quantity and is represented by **d.**

Displacement is the shortest distance between two points which has magnitude and direction.

SPEED AND VELOCITY

What information do we get by knowing the speed of a moving object?

Speed of an object is the rate at which it is moving. In other words, the distance moved by an object in unit time is its speed. This unit time may be a second, an hour, a day or a year.

The distance covered by an object in unit time is called its speed.

DO YOU KNOW?

Which is the fastest animal on the Earth?

Falcon can fly at a speed of 200 kmh^{-1}

$$\text{Speed} = \frac{\text{distance covered}}{\text{time taken}}$$

$$\text{Distance} = \text{speed x time}$$

$$\text{or} \qquad S = v\,t \quad \dots \quad \dots \quad \dots \quad \dots \quad (2.1)$$

Here S is the distance covered by the object, v is its speed and t is the time taken by it. Distance is a scalar; therefore, speed is also a scalar. SI unit of speed is metre per second (ms^{-1}).

UNIFORM SPEED

In equation 2.1, v is the average speed of a body during time f. It is because the speed of the body may be changing during the time interval t. However, if the speed of a body does not vary and has the same value then the body is said to possess uniform speed.

A body has uniform speed if it covers equal distances in equal intervals of time however short the interval may be.

VELOCITY

The velocity tells us not only the speed of a body but also the direction along which the body is moving. Velocity of a body is a vector quantity. It is equal to the displacement of a body in unit time.

The rate of displacement of a body is called its velocity.

$$\text{Velocity} = \frac{\text{displacement}}{\text{time taken}}$$

$$\text{or} \qquad \mathbf{v} = \frac{\mathbf{d}}{t}$$

$$\mathbf{d} = \mathbf{v}t \quad \dots \quad \dots \quad \dots \quad \dots (2.2)$$

Here **d** is the displacement of the body moving with velocity **v** in time t. SI unit of velocity is the same as speed i.e., metre per second (ms^{-1}).

UNIFORM VELOCITY

In equation 2.2, **v** is the average velocity of a body during time t. It is because the velocity of the

Cheetah can run at a speed of 70 kmh^{-1}.

DO YOU KNOW?

A motorway speed camera

A LIDAR gun is light detection and ranging speed gun. It uses the time taken by laser pulse to make a series of measurements of a vehicle's distance from the gun. The data is then used to calculate the vehicle's speed.

DO YOU KNOW?

A paratrooper attains a uniform velocity called terminal velocity with which it comes to ground,

body may be changing during the time interval *t.* However, in many cases the speed and direction of a body does not change. In such a case the body possesses uniform velocity. That is the velocity of a body during any interval of time has the same magnitude and direction. Thus

A body has uniform velocity if it covers equal displacement in equal intervals of time however short the interval may be.

EXAMPLE 2.2

A sprinter completes its 100 metre race in 12s. Find its average speed.

SOLUTION

Total distance = 100 m

Total time taken = 12 s

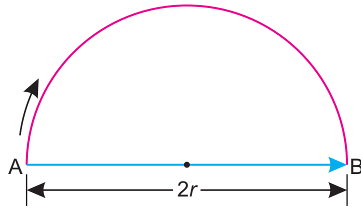
$$\text{Average speed} = \frac{\text{Total distance moved}}{\text{Total time taken}}$$

$$= \frac{100\,\text{m}}{12\,\text{s}} = 8.33\ \text{ms}^{-1}$$

Thus the speed of the sprinter is 8.33 ms^{-1} .

EXAMPLE 2.3

A cyclist completes half round of a circular track of radius 318 m in 1.5 minutes. Find its speed and velocity.



Radius of track r = 318 m

Time taken t = 1 min. 30 s = 90 s

Distance covered = $\pi \times$ radius

= 3.14×318 m = 999 m

Displacement = 2 r

= 2×318 m = 636 m

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

$$= \frac{999\,\text{m}}{90\,\text{s}} = 11.1\ \text{ms}^{-1}$$

$$\text{velocity} = \frac{\text{displacement}}{\text{time taken}}$$

$$= \frac{636\,\text{m}}{90\,\text{s}} = 7.07\ \text{ms}^{-1}$$

Thus speed of the cyclist is 11.1 ms^{-1} along the track and its velocity is about 7.1 ms^{-1} along the diameter AB of the track.

ACCELERATION

When does a body possess acceleration?

In many cases the velocity of a body changes due to a change either in its magnitude or direction or both. The change in the velocity of a body causes acceleration in it.

Acceleration is defined as the rate of change of velocity of a body.

$$\text{Acceleration} = \frac{\text{change in velocity}}{\text{time taken}}$$

$$\text{Acceleration} = \frac{\text{final velocity - initial velocity}}{\text{time taken}}$$

$$\mathbf{a} = \frac{\mathbf{v_f - v_i}}{t} \quad \ldots \quad \ldots \quad \ldots (2.3)$$

Taking acceleration as a, initial velocity as V_i, final velocity as v_f and t is the time interval. SI unit of acceleration is metre per second per second (ms^{-2}).

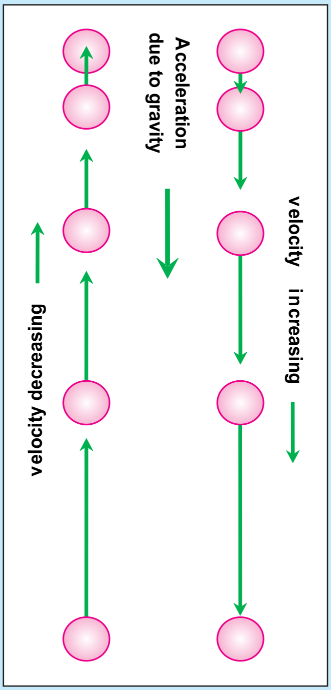
UNIFORM ACCELERATION

The average acceleration of a body given by equation 2.3 is **a** during time t. Let the time t is divided into many smaller intervals of time. If the rate of change of velocity during all these intervals remains constant then the acceleration **a** also remains constant. Such a body is said to possess uniform acceleration.

A body has uniform acceleration if it has equal changes in velocity in equal intervals of time however short the interval may be.

USEFUL INFORMATION

Acceleration of a moving object is in the direction of velocity if its velocity is increasing. Acceleration of the object is opposite to the direction of velocity if its velocity is decreasing.



Acceleration of a body is positive if its velocity increases with time. The direction of this acceleration is the same in which the body is moving without change in its direction. Acceleration of a body is negative if velocity of the body decreases. The direction of negative acceleration is opposite to the direction in which the body is moving. Negative acceleration is also called **deceleration** or **retardation.**

EXAMPLE 2.4

A car starts from rest. Its velocity becomes 20 ms in 8 s. Find its acceleration.

SOLUTION

Initial velocity v_i = $0\ \text{ms}^{-1}$

Final velocity v_f = $20\ \text{ms}^{-1}$

Time taken t = 8 s

as $$a = \frac{v_f - v_i}{t}$$

or $$a = \frac{20\ \text{ms}^{-1} - 0\ \text{ms}^{-1}}{8\ \text{s}}$$

$$= 2.5\ \text{ms}^{-2}$$

Thus the acceleration of the car is $2.5\ \text{ms}^{-2}$

EXAMPLE 2.5

Find the retardation produced when a car moving at a velocity of $30\ \text{ms}^{-1}$ slows down uniformly to $15\ \text{ms}^{-1}$ in 5s.

SOLUTION

Initial velocity v_i = $30\ \text{ms}^{-1}$

Final velocity v_f = $15\ \text{ms}^{-1}$

Change in velocity = $v_f - v_i$

$= 15\ \text{ms}^{-1} - 30\ \text{ms}^{-1}$

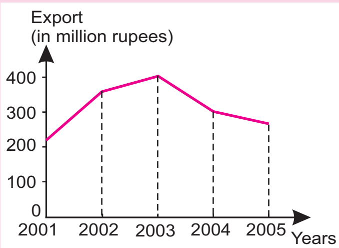
$= -15\ \text{ms}^{-1}$

Time taken t = 5 s

a = ?

DO YOU KNOW?

A graph may also be used in everyday life such as to show year-wise growth/decline of export, month-wise rainfall, a patient's temperature record or runs per over scored by a team and so on.



Export of rice from 2001-2005

Runs scored by a cricket team.

as Acceleration $= \dfrac{\text{change in velocity}}{\text{time interval}}$

or $$a = \frac{-15\ \text{ms}^{-1}}{5\ \text{s}} = -3\ \text{ms}^{-2}$$

Since negative acceleration is called as deceleration. Thus deceleration of the car is $3\ \text{ms}^{-2}$.

2.5 GRAPHICAL ANALYSIS OF MOTION

Graph is a pictorial way of presenting information about the relation between various quantities. The quantities between which a graph is plotted are called the variables. One of the quantities is called the independent quantity and the other quantity, the value of which varies with the independent quantity is called the dependent quantity.

DISTANCE-TIME GRAPH

It is useful to represent the motion of objects using graphs. The terms distance and displacement are used interchangeably when the motion is in a straight line. Similarly if the motion is in a straight line then speed and velocity are also used interchangeably. In a distance-time graph, time is taken along horizontal axis while vertical axis shows the distance covered by the object.

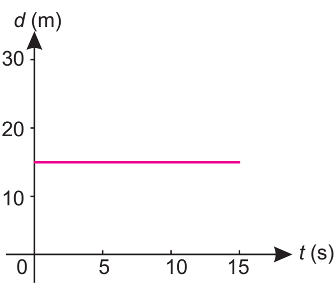


Figure 2.18: Distance-time graph when the object is at rest.

OBJECT AT REST

In the graph shown in figure 2.18, the distance moved by the object with time is zero. That is, the object is at rest. Thus a horizontal line parallel to time axis on a distance-time graph shows that speed of the object is zero.

OBJECT MOVING WITH CONSTANT SPEED

The speed of an object is said to be constant if it covers equal distances in equal intervals of time. The distance-time graph as shown in figure 2.19 is a straight line. Its slope gives the speed of the object. Consider two points A and B on the graph

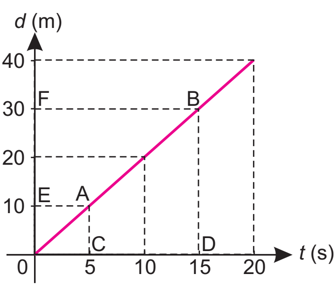


Figure 2.19: Distance time graph showing constant speed.

$$\text{Speed of the object} = \text{slope of line AB}$$

$$= \frac{\text{distance EF}}{\text{time CD}}$$

$$= \frac{20\ \text{m}}{10\ \text{s}} = 2\ \text{ms}^{-1}$$

The speed found from the graph is 2 m^{-1}

OBJECT MOVING WITH VARIABLE SPEED

When an object does not cover equal distances in equal intervals of time then its speed is not constant. In this case the distance-time graph is not a straight line as shown in figure 2.20. The slope of the curve at any point can be found from the slope of the tangent at that point. For example,

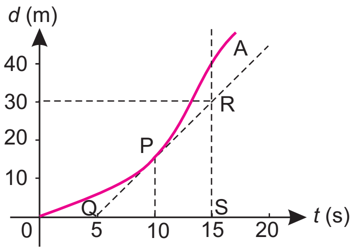


Figure 2.20: Distance- time graph showing variable speed.

$$\text{Slope of the tangent at P} = \frac{RS}{QS}$$

$$= \frac{30\ \text{m}}{10\ \text{s}} = 3\ \text{ms}^{-1}$$

Thus, speed of the object at P is 3 ms^{-1}. The speed is higher at instants when slope is greater; speed is zero at instants when slope is horizontal.

EXAMPLE 2.6

Figure 2.21 shows the distance-time graph of a moving car. From the graph, find

(a) the distance car has traveled.
(b) the speed during the first five seconds.
(c) average speed of the car.
(d) speed during the last 5 seconds.

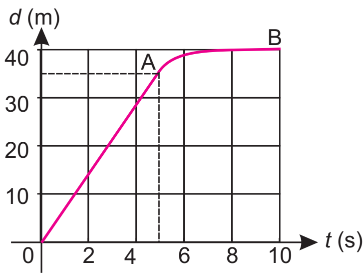


Figure 2.21: Distance-time graph of a car in example 2.6

SOLUTION

(a) Total distance travelled = 40 m

(b) Distance travelled during first 5s is 35 m

$$\therefore \quad \text{Speed} = \frac{35\ \text{m}}{5\ \text{s}}$$

$$= 7\ \text{ms}^{-1}$$

(c) $$\text{Average speed} = \frac{40\ \text{m}}{10\ \text{s}}$$

$$= 4\ \text{ms}^{-1}$$

(d) Distance moved during the last 5s = 5 m

$$\therefore \quad \text{Speed} = \frac{5\text{ m}}{5\text{ s}} = 1\text{ ms}^{-1}$$

SPEED-TIME GRAPH

In a speed-time graph, time is taken along x-axis and speed is taken along y-axis.

OBJECT MOVING WITH CONSTANT SPEED

When the speed of an object is constant (4 ms^{-1}) with time, then the speed-time graph will be a horizontal line parallel to time-axis along x-axis as shown in figure 2.22. In other words, a straight line parallel to time axis represents constant speed of the object.

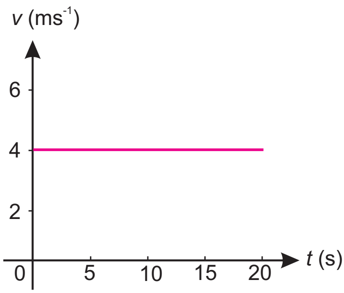


Figure 2.22: Speed-time graph showing constant speed.

OBJECT MOVING WITH UNIFORMLY CHANGING SPEED (uniform acceleration)

Let the speed of an object be changing uniformly. In such a case speed is changing at constant rate. Thus its speed-time graph would be a straight line such as shown in figure 2.23. A straight line means that the object is moving with uniform acceleration. Slope of the line gives the magnitude of its acceleration.

EXAMPLE 2.7

Find the acceleration from speed-time graph shown in figure 2.23.

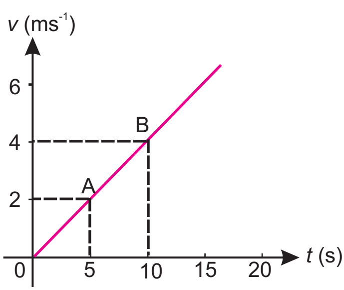


Figure 2.23: Graph of an object moving with unifrm acceleration.

SOLUTION

On the graph in figure 2.23, point A gives speed of the object as 2 ms^{-1} after 5 s and point B gives speed of the object as 4 ms^{-1} after 10 s

as acceleration = slope of AB

where slope = change in velocity/time interval

$$\therefore \quad \text{acceleration} = \frac{4\text{ ms}^{-1} - 2\text{ ms}^{-1}}{10\text{ s} - 5\text{ s}}$$

$$= \frac{2\text{ ms}^{-1}}{5\text{ s}} = 0.4\text{ ms}^{-2}$$

Speed-time graph in figure 2.23 gives acceleration of the object as $0.4\ ms^{-2}$.

EXAMPLE 2.8

Find the acceleration from speed-time graph shown in figure 2.24.

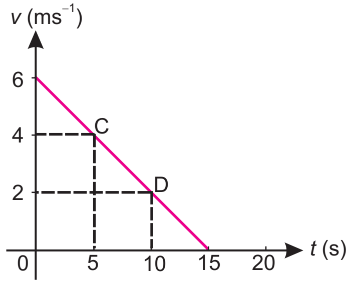


Figure 2.24: Graph of an object moving with uniform deceleration.

SOLUTION

The graph in figure 2.24 shows that the speed of the object is decreasing with time. The speed after 5s is $4\ ms^{-1}$ and it becomes $2\ ms^{-1}$ after 10 s.

as acceleration = slope of CD

$$= \frac{2\ ms^{-1} - 4\ ms^{-1}}{10\ s - 5\ s}$$

$$= -\frac{2\ ms^{-1}}{5\ s} \qquad = -0.4\ ms^{-2}$$

Speed-time graph in figure 2.24 gives negative slope. Thus, the object has deceleration of $0.4\ ms^{-2}$.

DISTANCE TRAVELLED BY A MOVING OBJECT

The area under a speed-time graph represents the distance travelled by the object. If the motion is uniform then the area can be calculated using appropriate formula for geometrical shapes represented by the graph.

EXAMPLE 2.9

A car moves in a straight line. The speed-time graph of its motion is shown in figure 2.25.

From the graph, find

(a) Its acceleration during the first 10 seconds.

(b) Its deceleration during the last 2 seconds.

(c) Total distance travelled.

(d) Average speed of the car during its journey.

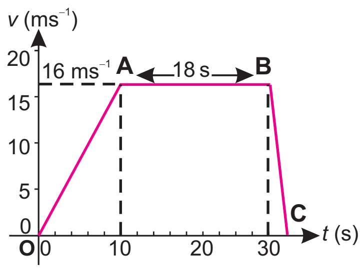


Figure 2.25: Speed time graph of a car during 30 seconds.

SOLUTION

(a) Acceleration during the first 10 seconds

$$= \frac{\text{change in velocity}}{\text{time taken}}$$

$$= \frac{16\ \text{ms}^{-1} - 0\ \text{ms}^{-1}}{10\ \text{s}}$$

$$= 1.6\ \text{ms}^{-2}$$

(b) Acceleration during the last 2 seconds

$$= \frac{0\ \text{ms}^{-1} - 16\ \text{ms}^{-1}}{2\ \text{s}}$$

$$= -8\ \text{ms}^{-2}$$

(c) Total distance travelled

= area under the graph (trapezium OABC)

$$= \frac{1}{2}(\text{sum of parallel sides}) \times \text{height}$$

$$= \frac{1}{2}(18\ \text{s} + 30\ \text{s}) \times (16\ \text{ms}^{-1})$$

$$= \frac{1}{2}(48\ \text{s}) \times (16\ \text{ms}^{-1})$$

$$= 384\ \text{m}$$

(d) $$\text{Average speed} = \frac{\text{Total distance covered}}{\text{Time taken}}$$

$$= \frac{384\ \text{m}}{30\ \text{s}} = 12.8\ \text{ms}^{-1}$$

2.6 EQUATIONS OF MOTION

There are three basic equations of motion for bodies moving with uniform acceleration. These equations relate initial velocity, final velocity, acceleration, time and distance covered by a moving body. To simplify the derivation of these equations, we assume that the motion is along a straight line. Hence, we consider only the magnitude of displacements, velocities, and acceleration.

Consider a body moving with initial velocity v_i in a straight line with uniform acceleration a. Its

velocity becomes v_f after time *t*. The motion of body is described by speed-time graph as shown in figure 2.26 by line AB. The slope of line AB is acceleration a. The total distance covered by the body is shown by the shaded area under the line AB. Equations of motion can be obtained easily from this graph.

FIRST EQUATION OF MOTION

Speed-time graph for the motion of a body is shown in figure 2.26. Slope of line AB gives the acceleration a of a body.

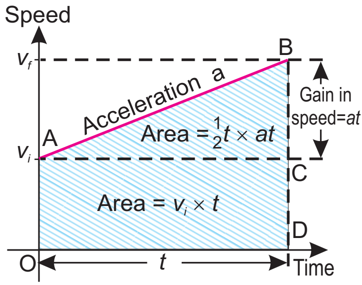


Figure 2.26: Speed-time graph. Area under the graph gives the distance covered by the body.

$$\text{Slope of line AB} = a = \frac{BC}{AC} = \frac{BD - CD}{OD}$$

as BD = v_f , CD = v_i and OD = t

$$\text{Hence} \quad a = \frac{v_f - v_i}{t}$$

$$\text{or} \quad v_f - v_i = at \quad \dots \dots \dots \dots (2.4)$$

$$\therefore \quad v_f = v_i + at \quad \dots \dots \dots (2.5)$$

SECOND EQUATION OF MOTION

In speed-time graph shown in figure 2.26, the total distance S travelled by the body is equal to the total area OABD under the graph. That is

Total distance S= area of (rectangle OACD + triangle ABC)

Area of rectangle OACD $= OA \times OD$

$= v_i \times t$

Area of triangle ABC $= \frac{1}{2}(AC \times BC)$

$= \frac{1}{2} t \times at$

Since Total area OABD = area of rectangle OACD + area of triangle ABC

Putting values in the above equation, we get

$$S = v_i\, t + \frac{1}{2}\, t \times at$$

$$S = v_i\, t + \frac{1}{2}\, at^2 \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2.6)$$

THIRD EQUATION OF MOTION

In speed-time graph shown in figure 2.26, the total distance S travelled by the body is given by the total area OABD under the graph.

$$\text{Total area OABD} = S = \frac{OA + BD}{2} \times OD$$

$$\text{or} \quad 2S = (OA + BD) \times OD$$

Multiply both sides by $\frac{BC}{OD}$, we get: $\left(\because \frac{BC}{OD} = a\right)$

$$2S \times \frac{BC}{OD} = (OA + BD) \times OD \times \frac{BC}{OD}$$

$$2S \times \frac{BC}{OD} = (OA + BD) \times BC \quad \ldots \quad (2.7)$$

Putting the values in the above equation 2.7, we get

$$2S \times a = (v_i + v_f) \times (v_f - v_i)$$

$$2aS = v_f^2 - v_i^2 \quad \ldots \quad \ldots \quad \ldots \quad (2.8)$$

EXAMPLE 2.10

A car travelling at 10 ms^{-1} accelerates uniformly at 2 ms^{-2}. Calculate its velocity after 5 s.

SOLUTION

$$v_i = 10\ ms^{-1}$$

$$a = 2\ ms^{-2}$$

$$t = 5s$$

$$v_f = ?$$

Using the equation (2.5), we get

$$v_f = v_i + at$$

$$v_f = 10\ ms^{-1} + 2\ ms^{-2} \times 5\ s$$

or $v_f = 20\ \text{ms}^{-1}$

The velocity of the car after 5 s is 20 ms

EXAMPLE 2.11

A train slows down from 80 kmh^{-1} with a uniform retardation of 2 ms^{-2} . How long will it take to attain a speed of 20 kmh^{-1}?

SOLUTION

$$v_i = 80\ \text{kmh}^{-1}$$

$$= \frac{80 \times 1000\ \text{m}}{60 \times 60\ \text{s}}$$

$$= 22.2\ \text{ms}^{-1}$$

$$v_f = 20\ \text{kmh}^{-1}$$

$$= \frac{20 \times 1000\ \text{m}}{60 \times 60\ \text{s}}$$

$$= 5.6\ \text{ms}^{-1}$$

$$a = -2\ \text{ms}^{-1}$$

$$t = ?$$

Using equation 2.4, we get

$$v_f = v_i + at$$

or $$t = \frac{v_f - v_i}{a}$$

$$\frac{5.6\ \text{ms}^{-1} - 22.2\ \text{ms}^{-1}}{-2\ \text{ms}^{-2}}$$

or $$t = 8.3\ \text{s}$$

Thus the train will take 8.3 s to attain the required speed.

EXAMPLE 2.12

A bicycle accelerates at 1 ms^{-2} from an initial velocity of 4 ms^{-1} for 10 s. Find the distance moved by it during this interval of time.

SOLUTION

$$v_i = 4\ \text{ms}^{-1}$$

$$a = 1\ \text{ms}^{-2}$$

$$t = 10\ \text{s}$$

$$S = ?$$

Applying equation (2.6), we get

USEFUL INFORMATION

- **To convert ms^{-1} to kmh^{-1}**

$1\ \text{ms}^{-1} = 0.001\ \text{km} \times 3600\ \text{h}^{-1}$

$= 3.6\ \text{kmh}^{-1}$

The Multiply acceleration in ms^{-1} by 3.6 to get speed in kmh^{-1} e.g.

$20\ \text{ms}^{-1} = 20 \times 3.6\ \text{kmh}^{-1}$

$= 72\ \text{kmh}^{-1}$

- **To convert kmh^{-1} to ms^{-1}**

$$1\ \text{kmh}^{-1} = \frac{1000\ \text{m}}{60 \times 60\ \text{s}} = \frac{10}{36}\ \text{ms}^{-1}$$

Thus multiply speed in kmh^{-1} by $\frac{10}{36}$ to get speed in ms^{-1} e.g.,

$$50\ \text{kmh}^{-1} = 50 \times \frac{10}{36}\ \text{ms}^{-1}$$

$= 13.88\ \text{ms}^{-1}$

Similarly

- **To convert ms^{-2} to kmh^{-2}**

Multiply acceleration in ms^{-2} by {(3600x3600)/1000}= 12960 to get its value in kmh^{-2}.

- **To convert kmh^{-2} to ms^{-2}**

Divide acceleration in kmh^{-2} by 12960 to get its value in ms^{-2}.

$$S = v_i t + \tfrac{1}{2} at^2$$
$$S = 4\ \text{ms}^{-1} \times 10\ \text{s} + \tfrac{1}{2} \times 1\ \text{ms}^{-2} \times (10\ \text{s})^2$$
or $$S = 40\ \text{m} + 50\ \text{m} = 90\ \text{m}$$

Thus, the bicycle will move 90 metres in 10 seconds.

EXAMPLE 2.13

A car travels with a velocity of 5 ms^{-1}. It then accelerates uniformly and travels a distance of 50 m. If the velocity reached is 15 ms^{-1}, find the acceleration and the time to travel this distance.

SOLUTION

$$v_i = 5\ \text{ms}^{-1}$$
$$S = 50\ \text{m}$$
$$v_f = 15\ \text{ms}^{-1}$$
$$a = ?$$
$$t = ?$$

Putting values in the third equation of motion, we get

$$2\,a\,S = v_f^2 - v_i^2$$
$$\therefore \quad 2\,a \times 50\ \text{m} = (15\ \text{ms}^{-1})^2 - (5\ \text{ms}^{-1})^2$$
$$(100\ \text{m})\,a = (225 - 25)\ \text{m}^2\text{s}^{-2}$$
$$a = \frac{200\ \text{m}^2\text{s}^{-2}}{100\ \text{m}}$$
or $$a = 2\ \text{ms}^{-2}$$

Using first equation of motion to find t, we get

$$v_f = v_i + at$$
$$\therefore \quad 15\ \text{ms}^{-1} = 5\ \text{ms}^{-1} + 2\ \text{ms}^{-2} \times t$$
$$15\ \text{ms}^{-1} - 5\ \text{ms}^{-1} = 2\ \text{ms}^{-2} \times t$$
or $$2\ \text{ms}^{-2} \times t = 10\ \text{ms}^{-1}$$
or $$t = \frac{10\ \text{ms}^{-1}}{2\ \text{ms}^{-2}}$$
$$= 5\ \text{s}$$

Thus, the acceleration of the car is 2 ms^{-2} and it takes 5 seconds to travel 50 m distance.

2.7 MOTION OF FREELY FALLING BODIES

Drop an object from some height and observe its motion. Does its velocity increase, decrease or remain constant as it approaches the ground?

Galileo was the first scientist to notice that all the freely falling objects have the same acceleration independent of their masses. He dropped various objects of different masses from the leaning tower of Pisa. He found that all of them reach the ground at the same time. The acceleration of freely falling bodies is called **gravitational acceleration.** It is denoted by ***g***. On the surface of the Earth, its value is approximately 10 ms^{-2}. For bodies falling down freely ***g*** is positive and is negative for bodies moving up.

Figure 2.27: Learning Tower of Pisa

EXAMPLE 2.14

A stone is dropped from the top of a tower. The stone hits the ground after 5 seconds. Find

- the height of the tower.
- the velocity with which the stone hits the ground.

SOLUTION

Initial velocity v, = 0

Gravitational acceleration g = 10 ms^{-2}

$t = 5$ s

$S = h = ?$

$v_f = ?$

(a) Applying the equation

$h = v_i t + ½ g t^2$, we get

$h = 0 \times 5\text{ s} + ½ \times 10\text{ ms}^{-2} \times (5\text{ s})^2$

or $h = 0 + 125$ m

$\therefore h = 125$ m

(b) Applying the equation

$v_f^2 - v_i^2 = 2gh$

$v_f^2 - (0)^2 = 2 \times 10\text{ ms}^{-2} \times 125\text{ m}$

$v_f^2 = 2500\text{ m}^2\text{s}^{-2}$

EQUATIONS OF MOTION FOR BODIES MOVING UNDER GRAVITY

$v_f = v_i + gt$

$h = v_i t + \frac{1}{2} gt^2$

$2gh = v_f^2 - v_i^2$

$$\therefore \quad v_f = 50\ \text{ms}^{-1}$$

Thus the height of the tower is 125 metres and it will hit the ground with a velocity of 50 ms^{-1}.

EXAMPLE 2.15

A boy throws a ball vertically up. It returns to the ground after 5 seconds. Find

(a) the maximum height reached by the ball.

(b) the velocity with which the ball is thrown up.

SOLUTION

Initial velocity (upward) $v_i = ?$

Gravitational acceleration $g = -10\ \text{ms}^{-2}$

Time for up and down motion $t_o = 5\ \text{s}$

Velocity at maximum height $v_f = 0$

$S = h = ?$

As the acceleration due to gravity is uniform, hence the time t taken by the ball to go up will be equal to the time taken to come down = ½ t_o

$$\text{or} \quad t = 1/2 \times 5\ \text{s} = 2.5\ \text{s}$$

(b) applying the equation (2.5), we get

$$v_f = v_i + g\,t$$

$$0 = v_i - 10\ \text{ms}^{-2} \times 2.5\ \text{s}$$

$$= v_i - 25\ \text{ms}^{-1}$$

$$\therefore \quad v_i = 25\ \text{ms}^{-1}$$

(a) Applying the equation (2.6), we get

$$h = v_i t + 1/2\, g\, t^2$$

$$h = 25\ \text{ms}^{-1} \times 2.5\ \text{s} - 10\ \text{ms}^{-2} \times (2.5\ \text{s})^2$$

$$\text{or} \quad h = 62.5\ \text{m} - 31.25\ \text{m} = 31.25\ \text{m}$$

Thus, the ball was thrown up with a speed of 25 ms^{-1} and the maximum height to which the ball rises is 31.25 m.

SUMMARY

- A body is said to be at rest, if it does not change its position with respect to its surroundings.
- A body is said to be in motion, if it changes its position with respect to its surroundings.
- Rest and motion are always relative. There is no such thing as absolute rest or absolute motion.
- Motion can be divided into the following three types.
  - Translatory motion: In which a body moves without any rotation.
  - Rotatory motion: In which a body spins about its axis.
  - Vibratory motion: In which a body moves to and fro about its mean position.
- Physical quantities which are completely described by their magnitude only are known as scalars.
- Physical quantities which are described by their magnitude and direction are called vectors.
- Position means the location of a certain place or object from a reference point.
- The shortest distance between two points is called the displacement.
- The distance travelled in any direction by a body in unit time is called speed.
- If the speed of a body does not change with time then its speed is uniform.
- Average speed of a body is the ratio of the total distance covered to the total time taken.
- We define velocity as rate of change of displacement or speed in a specific direction.
- Average velocity of a body is defined as the ratio of its net displacement to the total time.
- If a body covers equal displacements in equal intervals of time, however small the interval may be, then its velocity is said to be uniform.
- The rate of change of velocity of a body is called acceleration.
- A body has uniform acceleration if it has equal changes in its velocity in equal intervals of time, however small the interval may be.
- Graph is a pictorial way of describing information as to how various quantities are related to each other.
- Slope of the distance-time graph gives the speed of the body.
- Distance - time graphs provide useful information about the motion of an object. Slope of the displacement-time graph gives the velocity of the body.
- Distance covered by a body is equal to area under speed - time graph.
- Speed-time graph is also useful for studying motion along a straight line.
- The distance travelled by a body can also be found from the area under a velocity - time graph if the motion is along a straight line.

✦ Equations of motion for uniformly accelerated motion are:

- $v_f = v_i + at$
- $S = v_i t + \frac{1}{2} at^2$
- $2aS = v_f^2 - v_i^2$

✦ When a body is dropped freely it falls down with an acceleration towards Earth. This acceleration is called acceleration due to gravity and is denoted by *g*. The numerical value of *g* is approximately 10 ms^{-2} near the surface of the Earth.

QUESTIONS

2.1 Encircle the correct answer v. from the given choices:

i. A body has translatory motion if it moves along a

(a) straight line
(b) circle
(c) line without rotation
(d) curved path

ii. The motion of a body about an [VL] axis is called

(a) circular motion
(b) rotatory motion
(c) vibratory motion
(d) random motion

iii. Which of the following is a vector quantity?

(a) speed (b) distance
(c) displacement (d) power

iv. If an object is moving with constant speed then its distance-time graph will be a straight line.

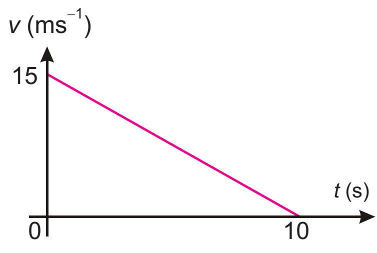
(a) along time-axis
(b) along distance-axis
(c) parallel to time-axis
(d) inclined to time-axis

v. A straight line parallel to time-axis on a distance-time graph tells that the object is

(a) moving with constant speed
(b) at rest
(c) moving with variable speed
(d) in motion

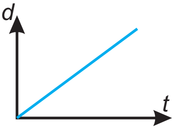
vi. The speed-time graph of a car is shown in the figure, which of the following statement is true?

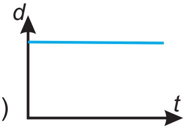
(a) car has an acceleration of 1.5 m^{-2}
(b) car has constant speed of 7.5 ms^{-1}
(c) distance travelled by the car is 75 m
(d) average speed of the car is 15 ms^{-1}

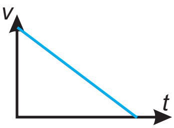


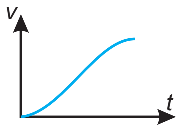
(vi) Speed-time graph of a car.

vii. Which one of the following graphs is representing uniform acceleration?

(a)


(b)


(c)


(d)


viii. By dividing displacement of a moving body with time, we obtain

(a) speed (b) acceleration

(c) velocity (d) deceleration

ix. A ball is thrown vertically upward. Its velocity at the highest point is :

(a) -10 ms^{-1} (b) zero

(c) 10 ms^{-2} (d) none of these

x. A change in position is called:

(a) speed (b) velocity

(c) displacement (d) distance

xi. A train is moving at a speed of 36 kmh^{-1}. Its speed expressed in ms^{-1} is:

(a) 10 ms^{-1} (b) 20 ms^{-1}

(c) 25 ms^{-1} (d) 30 ms^{-1}

xii. A car starts from rest. It acquires a speed of 25 ms^{-1} after 20 s. The distance moved by the car during this time is:

(a) 31.25 m (b) 250 m

(c) 500 m (d) 5000 m

2.2 Explain translatory motion and give examples of various types of translatory motion.

2.3 Differentiate between the following:

(i) Rest and motion.

(ii) Circular motion and rotatory motion.

(iii) Distance and displacement

(iv) Speed and velocity.

(v) Linear and random motion.

(vi) Scalars and vectors.

2.4 Define the terms speed, velocity, and acceleration.

2.5 Can a body moving at a constant speed have acceleration?

2.6 How do riders in a Ferris wheel possess translatory motion but not rotatory motion?

2.7 Sketch a distance-time graph for a body starting from rest. How will you determine the speed of a body from this graph?

2.8 What would be the shape of a speed - time graph of a body moving with variable speed?

2.9 Which of the following can be obtained from speed - time graph of a body?

(i) Initial speed.

(ii) Final speed.

(iii) Distance covered in time *t*.

(iv) Acceleration of motion.

2.10 How can vector quantities be represented graphically?

2.11 Why vector quantities cannot be added and subtracted like scalar quantities?

2.12 How are vector quantities important to us in our daily life?

2.13 Derive equations of motion for uniformly accelerated rectilinear motion.

2.14 Sketch a velocity - time graph for the motion of the body. From the graph explaining each step, calculate total distance covered by the body.

PROBLEM

2.1 A train moves with a uniform velocity of 36 kmh^{-1} for 10 s. Find the distance travelled by it. (100 m)

2.2 A train starts from rest. It moves through 1 km in 100 s with uniform acceleration. What will be its speed at the end of 100 s.

(20 ms^{-1})

2.3 A car has a velocity of 10 ms^{-1}. It accelerates at 0.2 ms^{-2} for half minute. Find the distance travelled during this time and the final velocity of the car.

(390 m, 16 ms^{-1})

2.4 A tennis ball is hit vertically upward with a velocity of 30 ms^{-1}. It takes 3 s to reach the highest point. Calculate the maximum height reached by the ball. How long it will take to return to ground?

(45 m, 6 s)

2.5 A car moves with uniform velocity of 40 ms"[1] for 5 s. It comes to rest in the next 10 s with uniform deceleration. Find (i) deceleration (ii) total distance travelled by the car.

(-4 ms^{-2}, 400 m)

2.6 A train starts from rest with an acceleration of 0.5 ms^{-2}. Find its speed in kmh^{-2}, when it has moved through 100 m. (36 kmh^{-2})

2.7 A train staring from rest, accelerates uniformly and attains a velocity 48 kmh^{-1} in 2 minutes. It travels at this speed for 5 minutes. Finally, it moves with uniform retardation and is stopped after 3 minutes. Find the total distance travelled by the train. (6000 m)

2.8 A cricket ball is hit vertically upwards and returns to ground 6 s later. Calculate (i) maximum height reached by the ball, (ii) initial velocity of the ball.

(45 m, 30 ms^{-1})

2.9 When brakes are applied, the speed of a train decreases from 96 kmh^{-1} to 48 kmh^{-1} in 800 m. How much further will the train move before coming to rest? (Assuming the retardation to be constant). (266.66 m)

2.10 In the above problem, find the time taken by the train to stop after the application of brakes.

(80 s)

Unit 3

Dynamics

STUDENT'S LEARNING OUTCOMES

After studying this unit, the students will be able to:

- define momentum, force, inertia, friction and centripetal force.
- solve problems using the equation Force = change in momentum / change in time.
- explain the concept of force by practical examples of daily life.
- state Newton's laws of motion.
- distinguish between mass and weight and solve problems using $F = ma$, and $w = mg$.
- calculate tension and acceleration in a string during motion of bodies connected by the string and passing over frictionless pulley using second law of motion.
- state the law of conversation of momentum.
- use the principle of conservation of momentum in the collision of two objects.
- determine the velocity after collision of two objects using the law of conservation of momentum.
- explain the effect of friction on the motion of a vehicle in the context of tyre surface, road conditions including skidding, braking force.
- demonstrate that rolling friction is much lesser than sliding friction.
- list various methods to reduce friction.

This unit is built on
Force and Motion
- Science-IV

This unit is leads to:
Motion and Force
- Physics-XI

Major Concepts

3.1 Momentum

3.2 Newton's laws of motion

3.3 Friction

3.4 Uniform circular motion

- explain that motion in a curved path is due to a perpendicular force on a body that changes direction of motion but not speed.
- calculate centripetal force on a body moving in a circle using mv^2/r.
- state what will happen to you while you are sitting inside a bus when the bus
  - (i) starts moving suddenly
  - (ii) stops moving suddenly
  - (iii) turns a corner to the left suddenly
- write a story about what may happen to you when you dream that all frictions suddenly disappeared. Why did your dream turn into a nightmare?

INVESTIGATION SKILLS

The students will be able to:

- identify the relationship between load and friction by sliding a trolley carrying different loads with the help of a spring balance on different surfaces.

SCIENCE, TECHNOLOGY AND SOCIETY CONNECTION

The students will be able to:

- identify the principle of dynamics with reference to the motion of human beings, objects, and vehicles (e.g. analyse the throwing of a ball, swimming, boating and rocket motion).
- identify the safety devices (such as packaging of fragile objects, the action of crumple zones and seatbelts) utilized to reduce the effects of changing momentum.
- describe advantages and disadvantages of friction in real - world situations, as well as methods used to increase or reduce friction in these situations (e.g. advantages of friction onthe surface of car tyres (tyre tread), cycling parachute, knots in string; disadvantages of friction, and methods for reducing friction

Figure 3.1: The food vendor on move

between moving parts of industrial machines and on wheels spinning on axles).

- identify the use of centripetal force in (i) safe driving by banking roads (ii) washing machine dryer (iii) cream separator.

In kinematics, we have studied the changes in motion only. Our understanding about the changes in motion is of little value without knowing its causes. The branch of mechanics that deals with the study of motion of an object and the cause of its motion is called **dynamics.** In this unit, we shall study momentum and investigate what causes a change in the motion of a body and what role the mass of a body plays in its motion. This inquiry leads us to the concept of force. We shall also study the laws of motion and their applications.

Figure 3.2: Ball is turned into different direction as it is pushed by the batsman.

3.1 FORCE, INERTIA AND MOMENTUM

Newton's laws of motion are of fundamental importance in understanding the causes of motion of a body. Before we discuss these laws, it is appropriate to understand various terms such as force, inertia and momentum.

Figure 3.3: A boy is pushing the wall.

FORCE

We can open a door either by pushing or pulling it Figure 3.**1** shows a man pushing a cart. The push may move the cart or change the direction of its motion or may stop the moving cart. A batsman in figure 3.2 is changing the direction of a moving ball by pushing it with his bat.

A force may not always cause a body to move. Look at the picture shown in figure 3.3. A boy is pushing a wall and is thus trying to move it. Could he move the wall? A Goalkeeper needs a force to stop a ball coming to him as shown in figure 3.4. Thus, we understand that

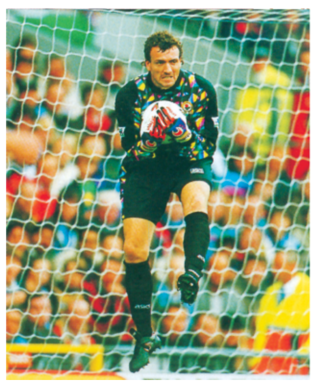


Figure 3.4: Goalkeeper is stopping the ball.

A force moves or tends to move, stops or tends to stop the motion of a body. The force can also change the direction of motion of a body.

What happens when you press a balloon?

You can cut an apple with a knife by pushing its sharp edge into the apple. Thus a force can also change the shape or size of a body on which it acts.

INERTIA

Galileo observed that it is easy to move or to stop light objects than heavier ones. Heavier objects are difficult to move or if moving then difficult to stop. Newton concluded that everybody resists to the change in its state of rest or of uniform motion in a straight line. He called this property of matter as inertia. He related the inertia of a body with its mass; greater is the mass of a body greater is its inertia.

Inertia of a body is its property due to which it resists any change in its state of rest or motion.

Let us perform an experiment to understand inertia.

Figure 3.5: The coin fails into the glass as the card flicks away.

EXPERIMENT 3.1

Take a glass and cover it with a piece of cardboard. Place a coin on the cardboard as shown in figure 3.5. Now flick the card horizontally with a jerk of your finger.

Does the coin move with the cardboard?

The coin does not move with the cardboard due to inertia.

Where does the coin go as the cardboard flies away?

Consider another example of inertia. Cut a strip of paper. Place it on the table. Stack a few coins at its one end as shown in figure 3.6. Pull out the paper strip under the coins with a jerk.

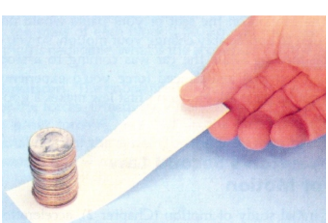


Figure 3.6: Coins stacked over remain undisturbed on pulling. the paper strip quickly

Do you succeed in pulling out the paper strip under the stacked coins without letting them to fall?
Why do the coins remain stacked on pulling out the paper strip quickly under the stack?

MOMENTUM

A bullet has a very small inertia due to its small mass. But why does its impact is so strong when it is fired from the gun?

On the other hand, the impact of a loaded truck on a body coming its way is very large even if the truck is moving slowly. To explain such situation, we define a new physical quantity called momentum.

Momentum of a body is the quantity of motion it possesses due to its mass and velocity.

The momentum *P* of a body is given by the product of its mass m and velocity *v*. Thus

$$P = mv \quad \ldots \ldots \ldots \ldots \ldots \quad (3.1)$$

Momentum is a vector quantity. Its SI unit is $kgms^{-1}$.

3.2 NEWTON'S LAWS OF MOTION

Newton was the first to formulate the laws of motion known as Newton's laws of motion.

NEWTON'S FIRST LAW OF MOTION

First law of motion deals with bodies which are either at rest or moving with uniform speed in a straight line. According to Newton's first law of motion, a body at rest remains at rest provided no net force acts on it. This part of the law is true as we observe that objects do not move by themselves unless someone moves them. For example, a book lying on a table remains at rest as long as no net force acts on it.

Net force is the resultant of all the forces acting on a body.

Similarly, a moving object does not stop moving by itself. A ball rolled on a rough ground stops earlier than that rolled on a smooth ground. It is because rough surfaces offer greater friction. If there would be no force to oppose the motion of a body then the moving body would never stop. Thus Newton's first law of motion states that:

A body continues its state of rest or of uniform motion in a straight line provided no net force acts on it.

DO YOU KNOW?

When a bus takes a sharp turn, passengers fall in the outward direction. It is due to inertia that they want to continue their motion in a straight line and thus fall outwards.

Since Newton's first law of motion deals with the inertial property of matter, therefore, Newton's first law of motion is also known as law of inertia.

We have observed that the passengers standing in a bus fall forward when its driver applies brakes suddenly. It is because the upper parts of their bodies tend to continue their motion, while lower parts of their bodies in contact with the bus stop with it. Hence, they fall forward.

NEWTON'S SECOND LAW OF MOTION

Newton's second law of motion deals with situations when a net force is acting on a body. It states that:

When a net force acts on a body, it produces acceleration in the body in the direction of the net force. The magnitude of this acceleration is directly proportional to the net force acting on the body and inversely proportional to its mass.

If a force produces an acceleration a in a body of mass m, then we can state mathematically that

$$a \propto F$$

and $$a \propto \frac{1}{m}$$

or $$a \propto \frac{F}{m}$$

or $$F \propto ma$$

Putting k as proportionality constant, we get

$$F = kma \quad \dots \quad \dots \quad \dots \quad (3.2)$$

In SI units, the value of k comes out to be 1. Thus Eq. 3.2 becomes

$$F = m\,a \quad \dots \quad \dots \quad \dots \quad (3.3)$$

SI unit of force is newton (N). According to Newton's second law of motion:

One newton (1 N) is the force that produces an acceleration of 1 ms^{-2} in a body of mass of 1 kg.

Thus, a force of one newton can be expressed as

$$1\text{N} = 1\text{ kg} \times 1\text{ ms}^{-2}$$

or $$1\text{N} = 1\text{ kg ms}^{-2} \quad \dots \quad \dots \quad (3.4)$$

EXAMPLE 3.1

Find the acceleration that is produced by a 20 N force in a mass of 8 kg.

SOLUTION

Here $m = 8\text{ kg}$

$F = 20\text{N}$

$a = ?$

using the formula $F = m\,a$

$$20\text{N} = 8\text{ kg} \times a$$

or $$a = \frac{20\text{N}}{8\text{kg}}$$

$$a = 2.5\ \frac{\text{kg ms}^{-2}}{\text{kg}}$$

$$= 2.5\text{ ms}^{-2}$$

Thus acceleration produced by the force is 2.5 ms^{-2} .

EXAMPLE 3.2

A force acting on a body of mass 5 kg produces an acceleration of 10 ms^{-2}. What acceleration the same force will produce in a body of mass 8 kg?

SOLUTION

Here $m_1 = 5\text{kg}$

$m_2 = 8\text{kg}$

$a_1 = 10\text{ ms}^{-2}$

$a_2 = ?$

Applying Newton's second law of motion, we get

$$F = m_1 a_1$$

$$F = m_2 a_2$$

Comparing the equations, we get

$$m_1 a_1 = m_2 a_2$$

$$(5\text{kg})\ (10\text{ms}^{-2}) = (8\text{kg})\ a_2$$

or $$a_2 = 6.25\text{ ms}^{-2}$$

Hence, the acceleration produced is 6.25 ms^{-2}.

EXAMPLE 3.3

A cyclist of mass 40 kg exerts a force of 200 N to move his bicycle with an acceleration of 3 ms^{-2}. How much is the force of friction between the road and the tyres?

SOLUTION

Here $m = 40$ kg

$a = 3\ ms^{-2}$

$F_o = 200$ N

Net Force $F = ?$

Force of friction $f = ?$

As net Force $F = m\,a$

$= 40\ kg \times 3\ ms^{-2}$

$= 120$ N

$\therefore$ Net force = Applied Force - Force of friction

120 N = 200N – f

Hence $f = 80$ N

Thus, the force of friction between the road and the tyres is 80 N.

MASS AND WEIGHT

Generally, mass and weight are considered similar quantities, but it is not correct. They are two different quantities. Mass of a body is the quantity of matter possessed by the body. It is a scalar quantity and does not change with change of place. It is measured by comparison with standard masses using a beam balance.

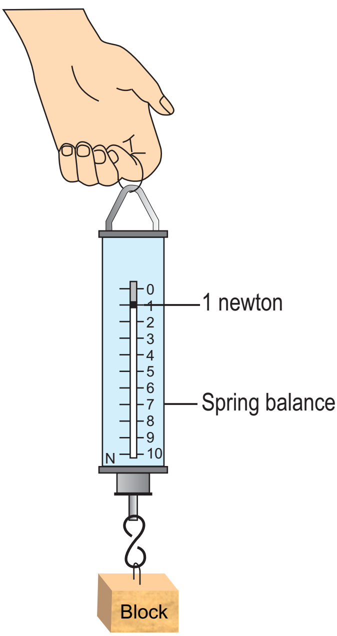


Figure 3.7: Spring balance is used to measure the force or weight of a body.

On the other hand, weight of a body is the force equal to the force with which Earth attracts it. It varies depending upon the value of ***g***, acceleration due to

gravity. Weight woi a body of mass m is related by the equation

$$w = mg \quad .... \quad (3.5)$$

Weight is a force and thus it is a vector quantity. Its SI unit is newton (N); the same as force. Weight is measured by a spring balance.

NEWTON'S THIRD LAW OF MOTION

Newton's third law of motion deals with the reaction of a body when a force acts on it. Let a body Aexerts a force on another body B, the body B reacts against this force and exerts a force on body A. The force exerted by body A on B is the action force whereas the force exerted by body B on A is called the reaction force. Newton's third law of motion states that:

To every action there is always an equal but opposite reaction.

According to this law, action is always accompanied by a reaction force and the two forces must always be equal and opposite. Note that action and reaction forces act on different bodies.

Consider a book lying on a table as shown in figure 3.8. The weight of the book is acting on the table in the downward direction. This is the action. The reaction of the table acts on the book in the upward direction. Consider another example. Take an air-filled balloon as shown in figure 3.9. When the balloon is set free, the air inside it rushes out and the balloon moves forward. In this example, the action is by the balloon that pushes the air out of it when set free. The reaction of the air which escapes out from the balloon acts on the balloon. It is due to this reaction of the escaping air that moves the balloon forward.

A rocket such as shown in figure 3.10 moves on the same principle. When its fuel burns, hot gases escape out from its tail with a very high speed. The

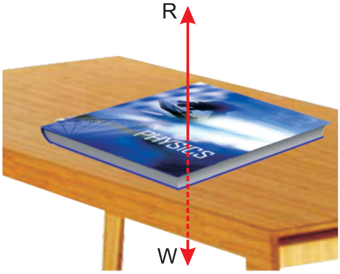


Figure 3.8: Action of the book and reaction on it.

Figure 3.9: Reaction of the air pushed out of the balloon moves it.

Figure 3.10: A Rocket taking off.

reaction of these gases on the rocket causes it to move opposite to the gases rushing out of its tail.

Quick Quiz

Stretch out your palm and hold a book on it.

1. How much force you need to prevent the book from falling?
2. Which is action?
3. Is there any reaction? If yes, then what is its direction?

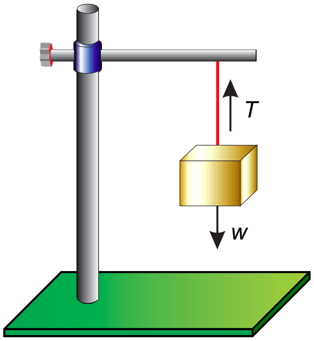


Figure 3.11: Weight of the block pulls the string downwards.

TENSION AND ACCELERATION IN A STRING

Consider a block supported by a string. The upper end of the string is fixed on a stand as shown in figure 3.11. Let *w* be the weight of the block. The block pulls the string downwards by its weight. This causes a tension *T* in the string. The tension *T* in the string is acting upwards at the block. As the block is at rest, therefore, the weight of the block acting downwards must be balanced by the upwards tension *T* in the string. Thus the tension *T* in the string must be equal and opposite to the weight w of the block.

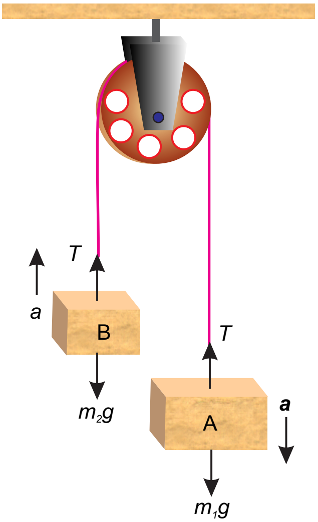


Figure 3.12: Bodies attached to the ends of a string that passes over a frictionless pulley.

VERTICAL MOTION OF TWO BODIES ATTACHED TO THE ENDS OF A STRING THAT PASSES OVER A FRICTIONLESS PULLEY

Consider two bodies A and B of masses m_1 and m_2 respectively. Let m_1 is greater than m_2. The bodies are attached to the opposite ends of an inextensible string. The string passes over a frictionless pulley as shown in figure 3.12. The body *A* being heavier must be moving downwards with some acceleration. Let this acceleration be *a*. At the same time, the body *B* attached to the other end of the string moves up with the same acceleration *a*. As the pulley is frictionless, hence tension will be the same throughout the string. Let the tension in the string be *T*.

Since the body *A* moves downwards, hence its weight m_1g is greater than the tension *T* in the string.

$\therefore$ Net force acting on body $A = m_1g - T$

According to Newton s second law of motion;

$$m_1 g - T = m_1 a \qquad \ldots \quad \ldots \quad \ldots \quad (3.6)$$

As body B moves upwards, hence its weight m_2g is less than the tension T in the string.

$\therefore$ Net force acting on body B = $T - m_2 g$

According to Newton's second law of motion;

$$T - m_2 g = m_2 a \qquad \ldots \quad \ldots \quad \ldots \quad (3.7)$$

Adding Eq. 3.6 and Eq.3.7, we get acceleration a.

$$a = \frac{m_1 - m_2}{m_1 + m_2} g \qquad \ldots \quad \ldots \quad (3.8)$$

Divide Eq. 3.7 by Eq. 3.6, to find tension T in the string.

$$T = \frac{2m_1 m_2}{m_1 + m_2} g \qquad \ldots \quad \ldots \quad (3.9)$$

The above arrangement is also known as Atwood machine. It can be used to find the acceleration *g* due to gravity using Eq 3.8,

$$g = \frac{2m_1 + m_2}{m_1 - m_2} a$$

EXAMPLE 3.4

Two masses 5.2 kg and 4.8 kg are attached to the ends of an inextensible string which passes over a frictionless pulley. Find the acceleration in the system and the tension in the string when both the masses are moving vertically.

SOLUTION

$$m_1 = 5.2 \text{ kg}$$
$$m_2 = 4.8 \text{ kg}$$

as $$a = \frac{m_1 - m_2}{m_1 + m_2} g$$

$$= \frac{5.2\,\text{kg} - 4.8\,\text{kg}}{5.2\,\text{kg} + 4.8\,\text{kg}} \times 10 \text{ ms}^{-2}$$

$$\therefore \quad a = 0.4 \text{ ms}^{-2}$$

as $$T = \frac{2m_1 m_2}{m_1 + m_2} g$$

DO YOU KNOW?

An Atwood machine is an arrangement of two objects of unequal masses such as shown in figure 3.12. Both the objects are attached to the ends of a string. The string passes over a frictionless pulley. This arrangement is sometime used to find the acceleration due to gravity.

$$= \frac{2 \times 5.2\,\text{kg} \times 4.8\,\text{kg}}{5.2\,\text{kg} + 4.8\,\text{kg}} \times 10\ \text{ms}^{-2}$$

$$\therefore \quad T = 50\ \text{N}$$

Thus the acceleration in the system is 0.4 ms^{-2} and tension in the string is 50 N.

MOTION OF TWO BODIES ATTACHED TO THE ENDS OF A STRING THAT PASSES OVER A FRICTIONLESS PULLEY SUCH THAT ONE BODY MOVES VERTICALLY AND THE OTHER MOVES ON A SMOOTH HORIZONTAL SURFACE

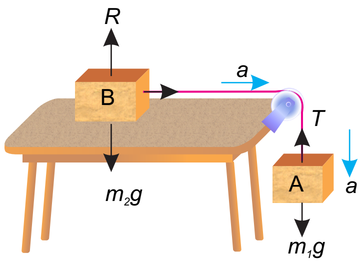


Figure 3.13: Motion of masses attached to a string that passes over a frictionless pulley.

Consider two bodies *A* and *B* of masses m_1 and m_2 respectively attached to the ends of an inextensible string as shown in figure 3.13. Let the body *A* moves downwards with an acceleration **a**. Since the string is inextensible, therefore, body B also moves over the horizontal surface with the same acceleration **a**. As the pulley is frictionless, hence tension *T* will be the same throughout the string.

Since body *A* moves downwards, therefore, its weight m_1g is greater than the tension *T* in the string.

Net force acting on body *A* = $m_1g - T$

According to Newton's second law of motion;

$$m_1 g - T = m_1 a \quad \ldots \quad \ldots \quad \ldots \quad (3.10)$$

The forces acting on body *B* are:

i. Weight m_2g of the body *B* acting downward.

ii. Reaction *R* of the horizontal surface acting on body *B* in the upwards direction.

iii. Tension *T* in the string pulling the body *B* horizontally over the smooth surface.

As body *B* has no vertical motion, hence resultant of vertical forces(m_2g and *R*) must be zero.

Thus, the net force acting on body *B* is *T*.

According to Newton's second law of motion;

$$T = m_2 a \quad \ldots \quad \ldots \quad \ldots \quad (3.11)$$

Adding Eqs. 3.10 and 3.11, we get acceleration a as

$$a = \frac{m_1}{m_1 + m_2} g \quad \ldots \quad \ldots \quad (3.12)$$

Putting the value of a in equations 3.11 to get tension T as

$$T = \frac{m_1 m_2}{m_1 + m_2} g \quad \ldots \quad \ldots \quad (3.13)$$

EXAMPLE 3.5

Two masses 4 kg and 6 kg are attached to the ends of an inextensible string which passes over a frictionless pulley such that mass 6 kg is moving over a frictionless horizontal surface and the mass 4 kg is moving vertically downwards. Find the acceleration in the system and the tension in the string.

SOLUTION

$$m_1 = 4 \text{ kg}$$

$$m_2 = 6 \text{ kg}$$

as $$a = \frac{m_1}{m_1 + m_2} g$$

$$= \frac{4 \text{ kg}}{4 \text{ kg} + 6 \text{ kg}} \times 10 \text{ ms}^{-2}$$

$$\therefore \quad a = 4 \text{ ms}^{-2}$$

as $$T = \frac{m_1 m_2}{m_1 + m_2} g$$

$$= \frac{4 \text{ kg} \times 6 \text{ kg}}{4 \text{ kg} + 6 \text{ kg}} \times 10 \text{ ms}^{-2}$$

$$\therefore \quad T = 24 \text{ N}$$

Thus the acceleration in the system is 4 ms^{-2} and tension in the string is 24N.

FORCE AND THE MOMENTUM

Consider a body of mass m moving with initial velocity v_i. Let a force F acts on the body which produces an acceleration a in it. This changes the velocity of the body. Let its final velocity after time becomes v_f. If P_i and P_f be the initial momentum and

USEFUL INFORMATION

Fragile objects such as glass wares etc. are packed with suitable materials such as styrofoam rings, balls, polythene sheets with air sacks etc.

Air enclosed in the cavities of these materials makes them flexible and soft. During any mishap, they increase the impact time on fragile objects. An increase in impact time lowers the rate of change of momentum and hence lessens the impact of force. This lowers the possible damage due to an accident.

USEFUL INFORMATION

In an accident at high speed, the impact force is very large due to the extremely short stopping time. For safety purposes, vehicles have rigid cages for passengers with crumple zones at their front and rear ends.

During an accident, crumple zones collapse. This increases the impact time by providing extra time for crumpling. The impact of force is highly reduced and saves the passengers from severe injuries.

final momentum of the body related to initial and final velocities respectively, then

$$P_i = mv_i$$

and $$P_f = mv_f$$

$\therefore$ Change in momentum = final momentum – initial momentum

or $$P_f - P_i = mv_f - mv_i$$

Thus the rate of change in momentum is given by:

$$\frac{P_f - P_i}{t} = \frac{mv_f - mv_i}{t}$$

$$= m\frac{v_f - v_i}{t}$$

since $\frac{v_f - v_i}{t}$ is the rate of change of velocity equal to the acceleration a produced by the force *F*.

$$\therefore \quad \frac{P_f - P_i}{t} = m\,a$$

According to Newton's second law of motion,

$$F = ma$$

or $$\frac{P_f - P_i}{t} = F \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3.14)$$

Equation 3.14 also defines force and states Newton's second law of motion as

When a force acts on a body, it produces an acceleration in the body and will be equal to the rate of change of momentum of the body.

SI unit of momentum defined by equation 3.14 is newton-second (Ns) which is the same as $kgms^{-1}$.

EXAMPLE 3.6

A body of mass 5 kg is moving with a velocity of $10ms^{-1}$. Find the force required to stop it in 2 seconds.

SOLUTION

$$m = 5\text{ kg}$$
$$v_i = 10\text{ ms}^{-1}$$
$$v_f = 0\text{ ms}^{-1}$$

$$
\begin{aligned}
t &= 2\ \text{s} \\
F &= ? \\
P_i &= 5\ \text{kg} \times 10\ \text{ms}^{-1} \\
&= 50\ \text{Ns} \\
P_f &= 5\ \text{kg} \times 0\ \text{ms}^{-1} \\
&= 0\ \text{Ns} \\
\text{since} \qquad F &= \frac{P_f - P_i}{t} \\
&= \frac{50\ \text{Ns} - 0\ \text{Ns}}{2\ \text{s}} \\
&= 25\ \text{N}
\end{aligned}
$$

Thus 25 N force is required to stop the body.

LAW OF CONSERVATION OF MOMENTUM

Momentum of a system depends on its mass and velocity. A system is a group of bodies within certain boundaries. An **isolated system** is a group of interacting bodies on which no external force is acting. If no unbalanced or net force acts on a system, then according to equation 3.14 its momentum remains constant. Thus the momentum of an isolated system is always conserved. This is the Law of Conservation of Momentum. It states that:

The momentum of an isolated system of two or more than two interacting bodies remains constant.

Consider the example of an air-filled balloon as described under the third law of motion. In this case, balloon and the air inside it form a system. Before releasing the balloon, the system was at rest and hence the initial momentum of the system was zero. As soon as the balloon is set free, air escapes out of it with some velocity. The air coming out of it possesses momentum. To conserve momentum, the balloon moves in a direction opposite to that of air rushing out.

Consider an isolated system of two spheres of masses m_1 and m_2 as shown in figure 3.14. They are moving in a straight line with initial velocities u_1 and u_2

USEFUL INFORMATION

In case of an accident, a person not wearing seatbelt will continue moving until stopped suddenly by something before him. This something may be a windscreen, another passenger or back of the seat in front of him/her. Seatbelts are useful in two ways:

- They provide an external force to a person wearing seatbelt.
- The additional time is required for stretching seat belts. This prolongs the stopping time for momentum to change and reduces the effect of collision.

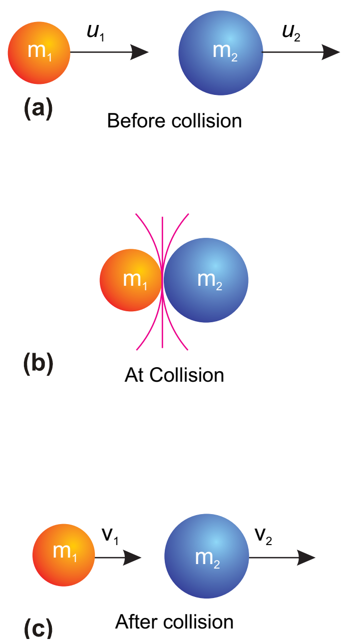


Figure 3.14: Collision of two bodies of spherical shapes.

respectively, such that u_1 is greater than u_2. Sphere of mass m_1 approaches the sphere of mass m_2 as they move.

Initial momentum of mass $m_1 = m_1u_1$ Initial momentum

of mass $m_2 = m_2u_2$ Total initial momentum of the system before collision $= m_1u_1+m_2u_2$ ... (3.15)

After sometime mass m_1 hits m_2 with some force. According to Newton's third law of motion, m_2 exerts an equal and opposite reaction force on m_1. Let their velocities become v_1 and v_2 respectively after collision. Then

Final momentum of mass $m_1 = m_1v_1$ Final

momentum of mass $m_2 = m_2v_2$

Total final momentum of the system after collision $= m_1v_1+m_2v_2$............. (3.16)

According to the law of conservation of momentum

$$\left(\begin{array}{l}\text{Total initial momentum of}\\ \text{the system before collision}\end{array}\right) = \left(\begin{array}{l}\text{Total final momentum}\\ \text{the system after collision}\end{array}\right)$$

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2 \quad \ldots \quad (3.17)$$

Equation 3.17 shows that the momentum of an isolated system before and after collisions remains the same which is the law of conservation of momentum. Law of conservation of momentum is an important law and has vast applications.

Consider a system of gun and a bullet. Before firing the gun, both the gun and bullet are at rest, so the total momentum of the system is zero. As the gun is fired, bullet shoots out of the gun and acquires momentum. To conserve momentum of the system, the gun recoils. According to the law of conservation of momentum, the total momentum of the gun and the bullet will also be zero after the gun is fired. Let *m* be the mass of the bullet and v be its velocity on firing the gun; *M* be the mass of the gun and *V* be the velocity

with which it recoils. Thus the total momentum of the gun and the bullet after the gun is fired will be;

$$\begin{pmatrix}\text{Total momentum of the}\\ \text{gun and the bullet after}\\ \text{the gun is fired}\end{pmatrix} = MV + mv \ldots \ldots \quad \ldots (3.18)$$

According to the law of conservation of momentum

$$\begin{pmatrix}\text{Total momentum of the}\\ \text{gun and the bullet after}\\ \text{the gun is fired}\end{pmatrix} = \begin{pmatrix}\text{Total momentum of the}\\ \text{gun and the bullet before}\\ \text{the gun is fired}\end{pmatrix}$$

$$\therefore \qquad MV + mv = 0$$

or $$MV = -mv$$

Hence $$V = -\frac{m}{M}\mathrm{v} \quad \ldots \quad \ldots \quad \ldots \quad (3.19)$$

Equation 3.19 gives the velocity V of the gun. Negative sign indicates that velocity of the gun is opposite to the velocity of the bullet, i.e., the gun recoils. Since mass of the gun is much larger than the bullet, therefore, the recoil is much smaller than the velocity of the bullet.

Rockets and jet engines also work on the same principle. In these machines, hot gases produced by burning of fuel rush out with large momentum. The machines gain an equal and opposite momentum. This enables them to move with very high velocities.

EXAMPLE 3.7

A bullet of mass 20 g is fired from a gun with a muzzle velocity 100 ms^{-1}. Find the recoil of the gun if its mass is 5 kg.

SOLUTION

$$m = 20\text{ g} = 0.02\text{ kg}$$

$$v = 100\text{ ms}^{-1}$$

$$M = 5\text{ kg}$$

$$V = ?$$

According to the law of conservation of momentum:

$$MV + mv = 0$$

Putting the values, we get

$$\therefore\ 5\ \text{kg} \times V + (0.02\ \text{kg}) \times (100\ \text{ms}^{-1}) = 0$$

$$\text{or} \quad 5\ \text{kg} \times V = -(0.02\ \text{kg}) \times (100\ \text{ms}^{-1})$$

$$\text{or} \quad V = -\frac{(0.2\ \text{kg}) \times (100\ \text{ms}^{-1})}{5\ \text{kg}}$$

$$= -0.4\ \text{ms}^{-1}$$

The negative sign indicates that the gun recoils i.e., moves in the backward direction opposite to the motion of the bullet with a velocity of 0.4 ms^{-1} .

Figure 3.15: A cyclist keeps on pedalling to overcome friction.

3.3 FRICTION

Have you noticed why a moving ball stops? Why bicycle stops when the cyclist stops pedalling?

Naturally there must be some force that stops moving objects. Since a force not only moves an object but also stops moving object.

The force that opposes the motion of moving objects is called friction.

Figure 3.16: To walk or to run friction is needed to push the ground backward

Friction is a force that comes into action as soon as a body is pushed or pulled over a surface. In case of solids, the force of friction between two bodies depends upon many factors such as nature of the two surfaces in contact and the pressing force between them. Rub your palm over different surfaces such as table, carpet, polished marble surface, brick, etc. You will find smoother is the surface, easier it is to move over the surface. Moreover, harder you press your palm over the surface, more difficult would it be to move.

Why friction opposes motion? No surface is perfectly smooth. A surface that appears smooth has pits and bumps that can be seen under a microscope. Figure 3.17 shows two wooden blocks with their polished surfaces in contact. A magnified view of two smooth surfaces in contact shows the gaps and

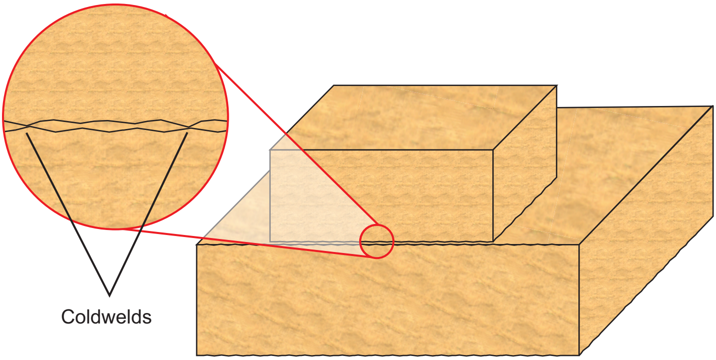


Figure 3.17: A magnified view of the two surfaces in contact.

contacts between them. The contact points between the two surfaces form a sort of **coldwelds.** These cold welds resist the surfaces from sliding over each other. Adding weight over the upper block increases the force pressing the surfaces together and hence, increases the resistance. Thus, greater is the pressing force greater will be the friction between the sliding surfaces.

Friction is equal to the applied force that tends to move a body at rest. It increases with the applied force. Friction can be increased to certain maximum value. It does not increase beyond this. The maximum value of friction is known as the **force of limiting friction (F_s).** It depends on the normal reaction (pressing force) between the two surfaces in contact. The ratio between the force of limiting friction F_s and the normal reaction R is constant. This constant is called the **coefficient of friction** and is represented by μ.

Thus $$\mu = \frac{F_s}{R} \quad \ldots \quad \ldots \quad \ldots \quad (3.20)$$

or $$F_s = \mu R \quad \ldots \quad \ldots \quad \ldots \quad (3.21)$$

If m be the mass of the block, then for horizontal surface;

$$R = mg \quad \ldots \quad \ldots \quad \ldots \quad (3.22)$$

Hence $$F_s = \mu mg \quad \ldots \quad \ldots \quad \ldots \quad (3.23)$$

Friction is needed to walk on the ground. It is risky to run on wet floor with shoes that have smooth soles. Athletes use special shoes that have extraordinary ground grip. Such shoes prevent them from slipping while running fast. What will we do to stop our bicycle? We will apply brakes. The rubber pads

TIDBITS

Pushing the opposite walls by palms and feet increases friction. This enables the boy to move up on the walls.

Coefficient of friction between some common materials

Materials	μ_s
Glass and Glass	0.9
Glass and Metal	0.5 - 0.7
Ice and Wood	0.05
Iron and Iron	1.0
Rubber and Concrete	0.6
Steel and Steel	0.8
Tyre and Road, dry	1
Tyre and Road, wet	0.2
Wood and Wood	0.25 - 0.6
Wood and Metal	0.2 - 0.6
Wood and Concrete	0.62

pressed against the rims provide friction. It is the friction that stops the bicycle.

QUICK QUIZ

1. Which shoe offer less friction?
2. Which shoe is better for walking on dry track?
3. Which shoe is better for jogging?
4. Which sole will wear out early?

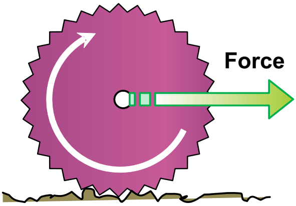


Figure 3.18: Friction may cause the body to roll.

Wheel is one of the most important inventions in the history of mankind. The first thing about a wheel is that it rolls as it moves rather than to slide. This greatly reduces friction. Why?

When the axle of a wheel is pushed, the force of friction between the wheel and the ground at the point of contact provides the reaction force. The reaction force acts at the contact points of the wheel in a direction opposite to the applied force. The wheel rolls without rupturing the cold welds. That is why the rolling friction is extremely small than sliding friction. The fact that rolling friction is less than sliding friction is applied in ball bearings or roller bearings to reduce losses due to friction.

Figure 3.19: A ball bearing

The wheel would not roll on pushing it if there would be no friction between the wheel and the ground. Thus, friction is desirable for wheels to roll over a surface. It is dangerous to drive on a wet road because the friction between the road and the tyres is very small. This increases the chance of slipping the tyres from the road. The threading on tyres is designed to increase friction. Thus, threading improves road grip and make it safer to drive even on wet road.

Figure 3.20: Threading on tyres provides good road grip.

A cyclist applies brakes to stop his/her bicycle. As soon as brakes are applied, the wheels stop rolling and begin to slide over the road. Since sliding friction is

much greater than rolling friction. Therefore, the cycle stops very quickly.

QUICK QUIZ

1. Why is it easy to roll a cylindrical eraser on a paper sheet than to slide it?
2. Do we roll or slide the eraser to remove the pencil work from our notebook?

BRAKING AND SKIDDING

The wheels of a moving vehicle have two velocity components:

(i) motion of wheels along the road.

(ii) rotation of wheels about their axis.

To move a vehicle on the road as well as to stop a moving vehicle requires friction between its tyres and the road. For example, if the road is slippery or the tyres are worn out then the tyres instead of rolling, slip over the road. The vehicle will not move if the wheels start slipping at the same point on the slippery road. Thus for the wheels to roll, the force of friction (gripping force) between the tyres and the road must be enough that prevents them from slipping.

Figure 3.21: A car skidding.

Similarly, to stop a car quickly, a large force of friction between the tyres and the road is needed. But there is a limit to this force of friction that tyres can provide. If the brakes are applied too strongly, the wheels of the car will lock up (stop turning) and the car will skid due to its large momentum. It will lose its directional control that may result in an accident. In order to reduce the chance of skidding, it is advisable not to apply brakes too hard that lock up their rolling motion especially at high speeds. Moreover, it is unsafe to drive a vehicle with worn out tyres.

Mini Exercise

1. In which case do you need smaller force and why?
   (i) rolling (ii) sliding
2. In which case it is easy for the tyre to roll over?
   (i) rough ground
   (ii) smooth ground

ADVANTAGES AND DISADVANTAGES OF FRICTION

Friction has the advantages as well as disadvantages. Friction is undesirable when moving at high speeds because it opposes the motion and thus

limits the speed of moving objects. Most of our useful energy is lost as heat and sound due to the friction between various moving parts of machines. In machines, friction also causes wear and tear of their moving parts.

However, sometimes friction is most desirable. We cannot write if there would be no friction between paper and the pencil. Friction enables us to walk on the ground. We cannot run on a slippery ground. A slippery ground offers very little friction. Hence, anybody who tries to run on a slippery ground may meet an accident. Similarly, it is dangerous to apply brakes with full force to stop a fast moving vehicle on a slippery road. Birds could not fly, if there is no air resistance. The reaction of pushed air enables the birds to fly. Thus in many situations, we need friction while in other situations we need to reduce it as much as possible.

DO YOU KNOW?

Friction is highly desirable when climbing up a hill.

Write a dream during which you are driving a car and suddenly the friction disappears. What happened next...?

Figure 3.22: Smooth air flow at high speeds reduces air resistance.

METHODS OF REDUCING FRICTION

The friction can be reduced by:

(i) making the sliding surfaces smooth.

(ii) making the fast moving objects a streamline shape (fish shape) such as cars, aero planes, etc. This causes the smooth flow of air and thus minimizes air resistance at high speeds.

(iii) Lubricating the sliding surfaces.

(iv) Using ball bearings or roller bearings .Because the rolling friction is lesser than the sliding friction.

Figure 3.23: Streamlining the bullet train reduces air resistance at high speed.

3.4 UNIFORM CIRCULAR MOTION

We come across many things in our daily life that are moving along circular path. Take a small stone. Tie it at one end of a string and keep the other end of the string in your hand as shown in figure 3.24.

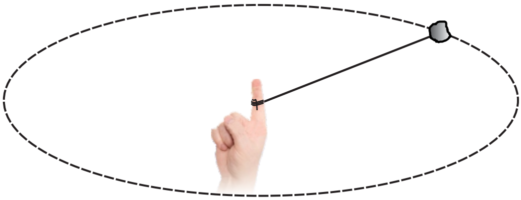


Figure 3.24: Circular motion of a stone attached with a string.

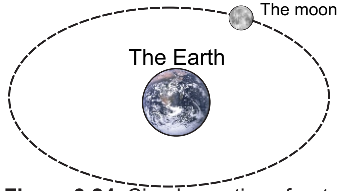


Figure 3.24: Circular motion of a stone attached with a string.

Now rotate the stone holding the string. The stone will move in a circular path. The motion of stone will be called as circular motion. Similarly, motion of the moon around the Earth is circular motion.

The motion of an object in a circular path is known as circular motion.

CENTRIPETAL FORCE

Consider a body tied at the end of a string moving with uniform speed in a circular path. A body has the tendency to move in a straight line due to inertia. Then why does the body move in a circle? The string to which the body is tied keeps it to move in a circle by pulling the body towards the centre of the circle. The string pulls the body perpendicular to its motion as shown in figure 3.26. This pulling force continuously changes the direction of motion and remains towards the centre of the circle. This centre seeking force is called the centripetal force. It keeps the body to move in a circle. Centripetal force always acts perpendicular to the motion of the body.

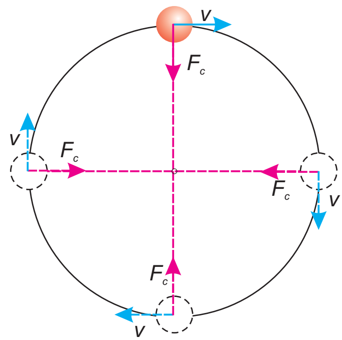


Figure 3.26: Centripetal force is always directed towards the centre and has no component in the direction of motion.

Centripetal force is a force that keeps a body to move in a circle.

Let us study the centripetal forces in the following examples:

(i) Figure 3.27 shows a stone tied to one end of a string rotating in a circle. The tension in the string provides the necessary centripetal force. It keeps the stone to remain in the circle. If the string is not strong enough to provide the necessary tension, it breaks and the stone

(a)

(b)

Figure 3.27 (a) A string provides necessary centripetal force.
(b) A string is unable to provide the required centripetal force.

moves away along a tangent to the circle as shown in figure 3.27(b).

(ii) The moon revolves around the Earth. The gravitational force of the Earth provides the necessary centripetal force.

Let a body of mass m moves with uniform speed v in a circle of radius r. The acceleration a_c produced by the centripetal force F_c is given by

$$\text{centripetal acceleration } a_c = \frac{v^2}{r} \quad \ldots \ldots (3.24)$$

According to Newton's second law of motion, the centripetal force F_c is given by

$$F_c = m\,a_c \quad \ldots \ldots \ldots (3.25)$$

$$F_c = \frac{mv^2}{r} \quad \ldots \ldots \ldots (3.26)$$

Equation (3.26) shows that the centripetal force needed by a body moving in a circle depends on the mass m of the body, square of its velocity v and reciprocal to the radius r of the circle.

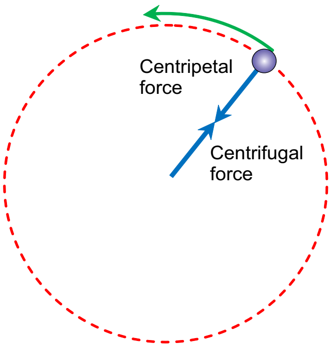
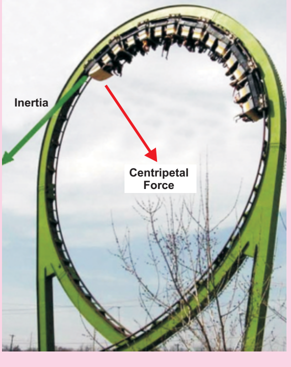


Figure 3.28: centripetal force acting on the stone and the centrifugal force acting on the string

CENTRIFUGAL FORCE

Consider a stone shown in figure 3.28 tied to a string moving in a circle. The necessary centripetal force acts on the stone through the string that keeps it to move in a circle. According to Newton's third law of motion, there exists a reaction to this centripetal force. Centripetal reaction that pulls the string outward is sometimes called the centrifugal force.

DO YOU KNOW?



While the coaster cars move around the loop, the track provides centripetal force preventing them to move away from the circle.

EXAMPLE 3.8

A stone of mass 100 g is attached to a string 1m long. The stone is rotating in a circle with a speed of 5 ms^{-1}. Find the tension in the string.

SOLUTION

$m = 100\text{ g} = 0.1\text{ kg}$

$v = 5\text{ ms}^{-1}$

$$r = 1\text{ m}$$

$$T = F_c = ?$$

Tension T in the string provides the necessary centripetal force given by

$$F_c = \frac{mv^2}{r}$$

$$\therefore \quad T = \frac{0.1\text{ kg} \times (5\text{ ms}^{-1})^2}{1\text{ m}}$$

$$T = 2.5\text{ N}$$

Thus, tension in the string will be equal to 2.5 N.

BANKING OF THE ROADS

When a car takes a turn, centripetal force is needed to keep it in its curved track. The friction between the tyres and the road provides the necessary centripetal force. The car would skid if the force of friction between the tyres and the road is not sufficient enough particularly when the roads are wet. This problem is solved by banking of curved roads. Banking of a road means that the outer edge of a road is raised. Imagine a vehicle on a curved road such as shown in figure 3.29. Banking causes a component of vehicle's weight to provide the necessary centripetal force while taking a turn. Thus banking of roads prevents skidding of vehicle and thus makes the driving safe.

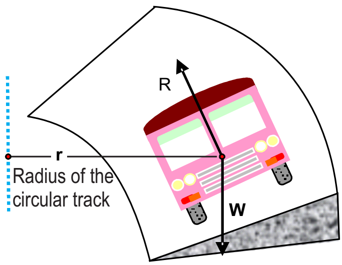


Figure 3.29: Outer edge of the curved road is elevated to prevent skidding.

WASHING MACHINE DRYER

The dryer of a washing machine is basket spinners. They have a perforated wall having large numbers of fine holes in the cylindrical rotor as shown in figure 3.30. The lid of the cylindrical container is closed after putting wet clothes in it. When it spins at high speed, the water from wet clothes is forced out through these holes due to lack of centripetal force.

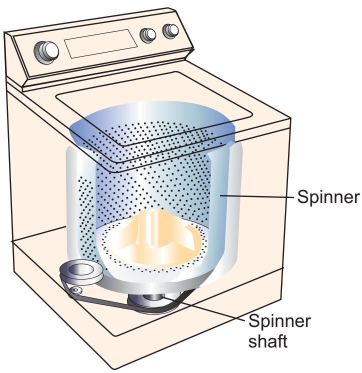


Figure 3.30: Dryer of washing machines has perforated wall.

CREAM SEPARATOR

Most modern plants use a separator to control the fat contents of various products. A separator is a high-speed spinner. It acts on the same principle of centrifuge machines. The bowl spins at very high

Figure 3.31: A Cream separator

speed causing the heavier contents of milk to move outward in the bowl pushing the lighter contents inward towards the spinning axis. Cream or butterfat is lighter than other components in milk. Therefore, skimmed milk, which is denser than cream is collected at the outer wall of the bowl. The lighter part (cream) is pushed towards the centre from where it is collected through a pipe.

SUMMARY

- A force is a push or pull. It moves or tends to move, stops or tends to stop the motion of a body.
- Inertia of a body is its property due to which it resists any change in its state of rest or uniform motion in a straight line.
- Momentum of a body is the quantity of motion possessed by the body. Momentum of a body is equal to the product of its mass and velocity
- The force that opposes the motion of a body is called friction.
- Newton's first law of motion states that a body continues its state of rest or of uniform motion in a straight line provided no net force acts on it.
- Newton's second law of motion states that when a net force acts on a body, it produces acceleration in the body in the direction of the net force. The magnitude of this acceleration is directly proportional to the net force acting on it and inversely proportional to its mass. Mathematically, $F = ma$.
- SI unit of force is newton (N). It is defined as the force which produces an acceleration of 1 ms"^{2} in a body of mass 1 kg.
- Mass of a body is the quantity of matter possessed by it. It is a scalar quantity. SI unit of mass is kilogramme (kg).
- Weight of a body is the force of gravity acting on it. It is a vector quantity. SI unit of weight is newton (N).
- Newton's third law of motion states that to every action there is always an equal and opposite reaction.
- The acceleration and tension in a system of two bodies attached to the ends of a string that passes over a frictionless pulley such that both move vertically are given by:

$$a = \frac{m_1 - m_2}{m_1 + m_2} g \; ; \; T = \frac{2m_1 m_2}{m_1 + m_2} g$$

- The acceleration and tension in a system of two bodies attached to the ends of a string that passes over a frictionless pulley such that one moves vertically and the other

moves on a smooth horizontal surface are given by:

$$a = \frac{m_1}{m_1 + m_2} g \;;\; T = \frac{m_1 m_2}{m_1 + m_2} g$$

- Law of conservation of momentum states that the momentum of an isolated system of two or more than two interacting bodies remains constant.
- A force between the sliding objects which opposes the relative motion between them is called friction.
- Rolling friction is the force of friction between a rolling body and a surface over which it rolls. Rolling friction is lesser than the sliding friction.
- The friction causes loss of energy in machines and much work has to be done in overcoming it. Moreover, friction leads to much wear and tear on the moving parts of the machine. The friction can be reduced by:
  - (i) Smoothing the sliding surfaces in contact.
  - (ii) Using lubricants between sliding surfaces.
  - (iii) Using ball bearings or roller bearings.
- The motion of a body moving along a circular path is called circular motion.
- The force which keeps the body to move in a circular path is called the centripetal force and is given.

  by $F_c = \dfrac{mv^2}{r}$
- According to Newton's third law of motion, there exists a reaction to the centripetal force. Centripetal reaction that pulls the string outward is sometimes called the centrifugal force.

QUESTIONS

3.1 **Encircle the correct answer from the given choices:**

i. Newton's first law of motion is valid only in the absence of:

(a) force (b) net force

(c) friction (d) momentum

ii. Inertia depends upon

(a) force (b) net force

(c) mass (d) velocity

iii. A boy jumps out of a moving bus. There is a danger for him to fall:

(a) towards the moving bus

(b) away from the bus

(c) in the direction of motion

(d) opposite to the direction of motion

iv. A string is stretched by two equal and opposite forces 10 N each. The tension in the string is

(a) zero (b) 5 N

(c) 10 N (d) 20 N

v. The mass of a body:

(a) decreases when accelerated

(b) increases when accelerated

(c) decreases when moving with high velocity

(d) none of the above.

vi. Two bodies of masses m_1 and m_2 attached to the ends of an inextensible string passing over a frictionless pulling such that both move vertically. The acceleration of the bodies is:

(a) $\frac{m_1 \times m_2}{m_1 + m_2} g$ (b) $\frac{m_1 - m_2}{m_1 + m_2} g$

(c) $\frac{m_1 + m_2}{m_1 - m_2} g$ (d) $\frac{2m_1 m_2}{m_1 + m_2} g$

vii. Which of the following is the unit of momentum?

(a) Nm (b) $kgms^{-2}$

(c) Ns (d) Ns^{-1}

viii. When horse pulls a cart, the action is on the:

(a) cart (b) Earth

© horse (d) Earth and cart

ix. Which of the following material lowers friction when pushed between metal plates?

(a) water (b) fine marble powder

(c) air (d) oil

3.2 Define the following terms:

(i) Inertia (ii) Momentum

(iii) Force (iv) Force of friction

(v) Centripetal force

3.3 What is the difference between:

(i) Mass and weight

(ii) Action and reaction

(iii) Sliding friction and rolling friction

3.4 What is the law of Inertia?

3.5 Why is it dangerous to travel on the roof of a bus?

3.6 Why does a passenger move outward when a bus takes a turn?

3.7 How can you relate a force with the change of momentum of a body?

3.8 What will be the tension in a rope that is pulled from its ends by two opposite forces 100 N each?

3.9 Action and reaction are always equal and opposite. Then how does a body move?

3.10 A horse pulls the cart. If the action and reaction are equal and opposite then how does the cart move?

3.11 What is the law of conservation of momentum?

3.12 Why is the law of conservation of momentum important?

3.13 When a gun is fired, it recoils. Why?

3.14 Describe two situations in which force of friction is needed.

3.15 How does oiling the moving parts of a machine lowers friction?

3.16 Describe ways to reduce friction.

3.17 Why rolling friction is less than sliding friction?

3.18 What you know about the following:

(i) Tension in a string
(ii) Limiting force of friction
(iii) Braking force
(iv) Skidding of vehicles
(v) Seatbelts
(vi) Banking of roads
(vii) Cream separator

3.19 What would happen if all friction suddenly disappears?

3.20 Why the spinner of a washing machine is made to spin at a very high speed?

PROBLEMS

3.1 A force of 20 N moves a body with an acceleration of 2 ms^{-2}. What is its mass? (10 kg)

3.2 The weight of a body is 147 N. What is its mass? (Take the value of g as 10 ms^{-2}) (14.7 kg)

3.3 How much force is needed to prevent a body of mass 10 kg from falling? (100 N)

3.4 Find the acceleration produced by a force of 100 N in a mass of 50 kg. (2 ms^{-2})

3.5 A body has weight 20 N. How much force is required to move it vertically upward with an acceleration of 2 ms^{-2}? (24 N)

3.6 Two masses 52 kg and 48 kg are attached to the ends of a string that passes over a frictionless pulley. Find the tension in the string and acceleration in the bodies when both the masses are moving vertically. (500 N, 0.4 ms^{-2})

3.7 Two masses 26 kg and 24 kg are attached to the ends of a string which passes over a frictionless pulley. 26 kg is lying over a smooth horizontal table. 24 N mass is moving vertically downward. Find the tension in the string and the acceleration in the bodies. (125 N, 4.8 ms^{-2})

3.8 How much time is required to change 22 Ns momentum by a force of 20 N? (1.1s)

3.9 How much is the force of friction between a wooden block of mass 5 kg and the horizontal marble floor? The coefficient of friction between wood and the marble is 0.6. (30 N)

3.10 How much centripetal force is needed to make a body of mass 0.5 kg to move in a circle of radius 50 cm with a speed 3 ms^{-1}? (**9** N)

Unit 4

Turning Effect of Forces

STUDENT'S LEARNING OUTCOMES

After studying this unit, the students will be able to:

- define like and unlike parallel forces.
- state head to tail rule of vector addition of forces/vectors.
- describe how a force is resolved into its perpendicular components.
- determine the magnitude and direction of a force from its perpendicular components.
- define moment of force or torque as moment = force x perpendicular distance from pivot to the line of action of force.
- explain the turning effect of force by relating it to everyday life.
- state the principle of moments.
- define the centre of mass and centre of gravity of a body.
- define couple as a pair of forces tending to produce rotation.
- prove that the couple has the same moments about all points.
- define equilibrium and classify its types by quoting examples from everyday life.
- state the two conditions for equilibrium of a body.

Conceptual linkage.

This unit is built on
Lever - Science-V
Machines - Science-VI
Kinematics - Physics-IX
Trigonometry - Maths-IX

This unit leads to:
Rotational Motion, Vectors and Equilibrium - Physics-XI

- solve problems on simple balanced systems when bodies are supported by one pivot only.
- describe the states of equilibrium and classify them with common examples.
- explain effect of the position of the centre of mass on the stability of simple objects.

INVESTIGATION SKILLS

The students will be able to:

- determine the position of centre of mass/gravity of regularly and irregularly shaped objects.

SCIENCE, TECHNOLOGY AND SOCIETY CONNECTION

The students will be able to:

- illustrate by describing a practical application of moment of force in the working of bottle opener, spanner, door/windows handles, etc.
- describe the working principle of see-saw.
- demonstrate the role of couple in the steering wheels and bicycle pedals.
- demonstrate through a balancing toy, racing car, etc. that the stability of an object can be improved by lowering the centre of mass and increasing the base area of the objects.

Major Concepts

4.1 Forces on bodies
4.2 Addition of Forces
4.3 Resolution of Forces
4.4 Moment of a Force
4.5 Principle of moments
4.6 Centre of mass
4.7 Couple
4.8 Equilibrium
4.9 Stability

Can the nut of the axle of a bike be loosened with hand? Normally we use a spanner as shown in figure 4.1. A spanner increases the turning effect of the force.

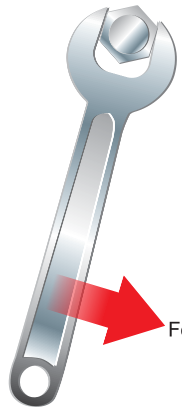


Figure 4.1: We can loose a nut with a spanner.

Look at the picture on the previous page. What is the joker doing? He is trying to balance himself on a wooden plank which is placed over a cylindrical pipe. Can we do the same? A baby gradually learns to stand by balancing herself. Women and children in the villages often carry pitchers with water on their heads such as shown in figure 4.2. With a little effort we can learn to balance a stick vertically up on our finger tip. Balanced objects are said to be in equilibrium. In this unit, we will learn many interesting concepts such as torque, equilibrium, etc. and their applications in daily life.

Figure 4.2: Children carrying pitchers on their heads.

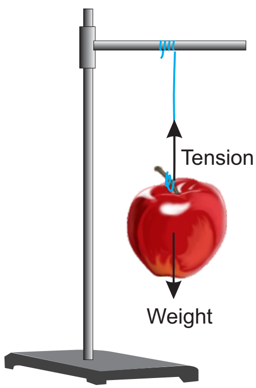
Figure 4.3: Like parallel forces.

4.1 LIKE AND UNLIKE PARALLEL FORCES

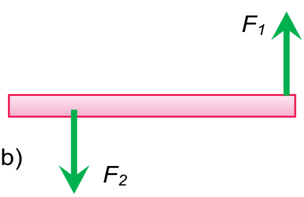
We often come across objects on which many forces are acting. In many cases, we find all or some of the forces acting on a body in the same direction. For example, many people push a bus to start it. Why all of them push it in the same direction? All these forces are applied in the same direction so these are all parallel to each other. Such forces which are parallel to each other are called parallel forces.

Figure 4.3 shows a bag with apples in it. The weight of each apple weight of the bag is due to the weight of all the apples in it. Since the weight of every apple in the bag is the force of gravity acting on it vertically downwards, therefore, weights of apples are the parallel forces. All these forces are acting in the same direction. Such forces are called like parallel forces.

Like parallel forces are the forces that are parallel to each other and have the same direction.



(a)



(b)

Figure 4.4: Unlike parallel forces
(**a**) along the same line
(**b**) can turn the object if not in line.

In figure 4.4(a), an apple is suspended by a string. The string is stretched due to weight of the apple. The forces acting on it are; weight of the apple acting vertically downwards and tension in the string pulling it vertically upwards. The two forces are parallel but opposite to each other. These forces are called unlike parallel forces. In figure 4.4(b), forces F_1 and F_2 are also unlike parallel forces, because they are parallel and opposite to each other. But F_1 and F_2 are not acting along the same line and hence they are capable to rotate the body.

Unlike parallel forces are the forces that are parallel but have directions opposite to each other.

4.2 ADDITION OF FORCES

Force is a vector quantity. It has both magnitude and direction; therefore, forces are not added by ordinary arithmetical rules. When forces are added, we get a resultant force.

A resultant force is a single force that has the same effect as the combined effect of all the forces to be added.

One of the methods for the addition of forces is a graphical method. In this method forces can be added by **head to tail rule** of vector addition.

HEAD TO TAIL RULE

Figure 4.5 shows a graphical method of vector addition. First select a suitable scale. Then draw the vectors of all the forces according to the scale; such as vectors **A** and **B.**

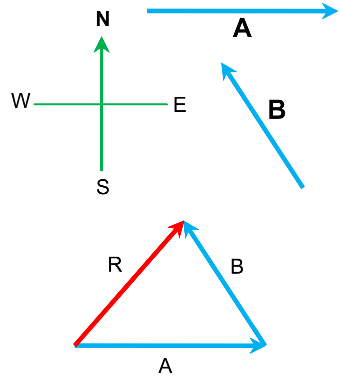


Figure 4.5: Adding vectors by head to tail rule.

Take any one of the vectors as first vector e.g., vector **A.** Then draw next vector **B** such that its tail coincides with the head of the first vector **A.** Similarly draw the next vector for the third force (if any) with its tail coinciding with the head of the previous vector and so on.

Now draw a vector **R** such that its tail is at the tail of vector **A,** the first vector, while its head is at the head of vector **B,** the last vector as shown in figure 4.5. Vector **R** represents the resultant force completely in magnitude and direction.

It should be noted that head to tail rule can be used to add any number of forces. The vector representing resultant force gives the magnitude and direction of the resultant force.

EXAMPLE 4.1

Find the resultant of three forces 12 N along x-axis, 8 N making an angle of 45° with x-axis and 8 N along y-axis.

SOLUTION

Here F_1 = 12 N along x-axis

F_2 = 8 N along 45° with x-axis

F_3 = 8 N along y-axis

Scale: 1 cm = 2 N

(i) Represent the forces by vectors $\mathbf{F_1}$, $\mathbf{F_2}$ and $\mathbf{F_3}$ according to the scale in the given direction.

(ii) Arrange these forces $\mathbf{F_1}$, $\mathbf{F_2}$ and $\mathbf{F_3}$. The tail of force $\mathbf{F_2}$ coincides with the head of force at point B as shown in figure 4.6. similarly the tail of force $\mathbf{F_3}$ coincides with the head of force $\mathbf{F_2}$ at point C.

(iii) Join point A the tail of the force $\mathbf{F_1}$ and point D the head of force $\mathbf{F_3}$. Let AD represents force **F.** According to head to tail rule, force **F** represents the resultant force.

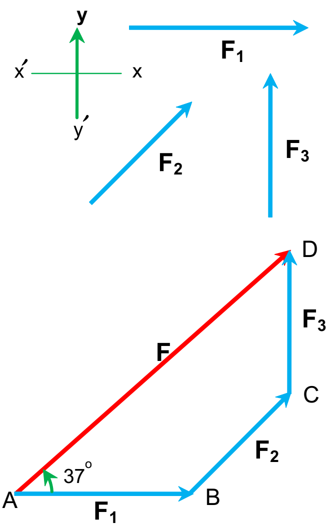
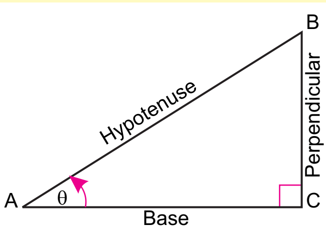


Figure 4.6: Adding forces by Head to tail rule.

Some Trigonometric Ratios

The ratios between any of its two sides of a right angled triangle are given certain names such as sine, cosine, etc. Consider a right angled triangle AABC having angle 6 at A.



$$\sin\theta = \frac{\text{Perpendicular}}{\text{Hypotenuse}} = \frac{BC}{AB}$$

$$\cos\theta = \frac{\text{Base}}{\text{Hypotenuse}} = \frac{AC}{AB}$$

$$\tan\theta = \frac{\text{Perpendicular}}{\text{Base}} = \frac{BC}{AC}$$

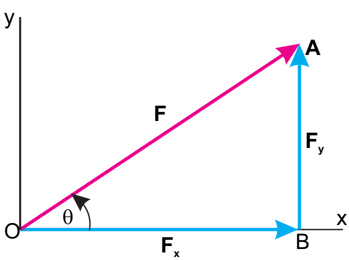


Figure 4.7: Resolution of a force

Ratio/θ	0°	30°	45°	60°	90°
sin θ	0	0.5	0.707	0.866	1
cos θ	1	0.866	0.707	0.5	0
tan θ	0	0.577	1	1.732	8

(iv) Measure AD and multiply it by 2 N cm^{-1} , the scale to find the magnitude of the resultant force **F.**

(v) Measure the angle ∠DAB using a protractor Which the force **F** makes with x-axis. This gives the direction of the resultant force.

4.3 RESOLUTION OF FORCES

The process of splitting up vectors (forces) into their component forces is called resolution of forces. If a force is formed from two mutually perpendicular components then such components are called its **perpendicular components.**

Splitting up of a force into two mutually perpendicular components is called the resolution of that force.

Consider a force **F** represented by line OA making an angle θ with x-axis as shown in figure 4.7.

Draw a perpendicular **AB** on x-axis from A. According to head to tail rule, **OA** is the resultant of vectors represented by **OB** and **BA.**

Thus $\quad$ **OA = OB + BA** … … … … … $\quad$ (4.1)

The components **OB** and **BA** are perpendicular to each other. They are called the perpendicular components of **OA** representing force **F.** Hence **OB** represents its x-component $\mathbf{F_x}$ and **BA** represents its y-component $\mathbf{F_{y}}$. Therefor, equation 4.1 can be written as

$$\mathbf{F} = \mathbf{F_x} + \mathbf{F_y} \quad \dots\dots\dots\dots \quad (4.2)$$

The magnitudes F_x *and* F_y of forces $\mathbf{F_x}$ and $\mathbf{F_y}$ can be found using the trigonometric ratios. In right angled triangle OBA

$$\text{Since} \quad \frac{F_x}{F} = \frac{OB}{OA} = \cos\theta$$

$$F_x = F\cos\theta \quad \dots\dots\dots\dots\dots \quad (4.3)$$

$$\text{Similarly} \quad \frac{F_y}{F} = \frac{BA}{OA} = \sin\theta$$

$$\therefore \quad F_y = F\sin\theta \quad \dots\dots\dots\dots\dots \quad (4.4)$$

Equations 4.3 and 4.4 give the perpendicular components F_x and F_y respectively.

EXAMPLE 4.2

A man is pulling a trolley on a horizontal road with a force of 200 N making 30° with the road. Find the horizontal and vertical components of its force.

SOLUTION

$F = 200$ N

$\theta = 30°$ with the horizontal

$F_x = ?$

$F_y = ?$

Since $F_x = F \cos\theta$

or $F_x = 200 \times \cos 30°$

$= 200 \times 0.866 = 173.2$ N

Similarly $F_y = F \sin\theta$

or $F_y = 200 \times \sin 30°$

$= 200 \times 0.5 = 100$ N

Thus, horizontal and vertical components of the pulling force are 173.2 N and 100 N respectively.

In a right angled triangle length of base is 4 cm and its perpendicular is 3 cm. Find:

(i) length of hypotenuse

(ii) $\sin\theta$

(iii) $\cos\theta$

(iv) $\tan\theta$

DETERMINATION OF A FORCE FROM ITS PERPENDICULAR COMPONENTS

Since a force can be resolved into two perpendicular components. Its reverse is to determine the force knowing its perpendicular components.

Consider $\mathbf{F_x}$ and $\mathbf{F_y}$ as the perpendicular components of a force **F**. These perpendicular components $\mathbf{F_x}$ and $\mathbf{F_y}$ are represented by lines **OP** and **PR** respectively as shown in figure 4.8.

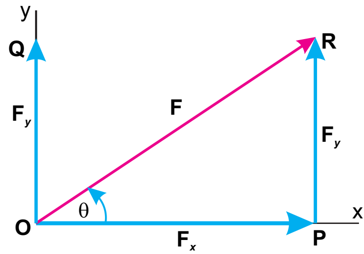


Figure 4.8: Determination of a force by its perpendicular components.

According to head to tail rule:

$$\mathbf{OR} = \mathbf{OP} + \mathbf{PR}$$

Thus **OR** will completely represent the force **F** whose x and y-components are $\mathbf{F_x}$ and $\mathbf{F_y}$ respectively. That is

$$\mathbf{F} = \mathbf{F_x} + \mathbf{F_y}$$

The magnitude of the force **F** can be determined using the right angled triangle OPR

$$(OR)^2 = (OP)^2 + (PR)^2$$

$$F^2 = F_x^{\,2} + F_y^{\,2}$$

Hence $$F = \sqrt{F_x^{\,2} + F_y^{\,2}} \quad \dots \dots \dots \dots (4.5)$$

The direction of force F with x-axis is given by

$$\tan\theta = \frac{PR}{OP} = \frac{F_y}{F_x}$$

$$\therefore \quad \theta = \tan^{-1}\frac{F_y}{F_x} \qquad \dots \dots \dots \dots \qquad (4.6)$$

Figure 4.9: It is easy to open and close the door by pulling or pushing it at its handle.

4.4 TORQUE OR MOMENT OF A FORCE

We open or close a door (Fig 4.9) by pushing or pulling it. Here push or pull turn the door about its hinge or axis of rotation. The door is opened or closed due to the turning effect of the force acting on it.

RIGID BODY

A body is composed of large number of small particles. If the distances between all pairs of particles of the body do not change by applying a force then it is called a rigid body. In other words, a rigid body is the one that is not deformed by force or forces acting on it.

AXIS OF ROTATION

Consider a rigid body rotating about a line. The particles of the body move in circles with their centres all lying on this line. This line is called the axis of rotation of the body.

Forces that produce turning effect are very common. Turning pencil in a sharpener, turning stopcock of a water tap, turning doorknob and so on are some of the examples where a force produces turning effect.

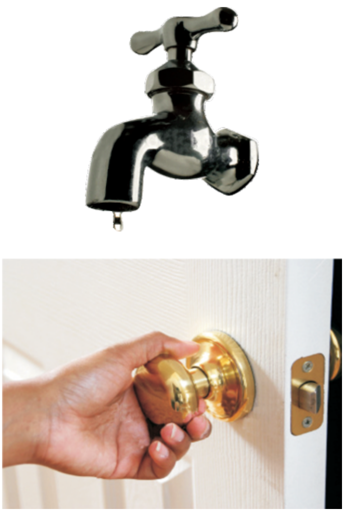


Figure 4.10: Turning effect of forces.

QUICK QUIZ

Name some more objects that work by the turning effects of forces.

The turning effect of a force is called torque or moment of the force.

Why the handle of a door is fixed near the outer edge of a door? We can open or close a door more easily by applying a force at the outer edge of a door rather than near the hinge. Thus, the location where the force is applied to turn a body is very important.

Let us study the factors on which torque or moment of a force depends. You might have seen that a mechanic uses a spanner as shown in figure 4.11 to loosen or tighten a nut or a bolt. A spanner having long arm helps him to do it with greater ease than the one

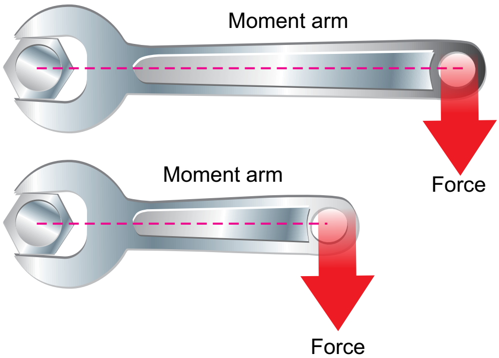


Figure 4.11: It is easy to tighten a nut using a spanner of longer arm than a spanner of shorter arm.

having short arm. It is because the turning effect of the force is different in the two cases. The moment produced by a force using a spanner of longer arm is greater than the torque produced by the same force but using a spanner of shorter arm.

LINE OF ACTION OF A FORCE

The line along which a force acts is called the line of action of the force. In figure 4.12, line BC is the line of action of force **F**.

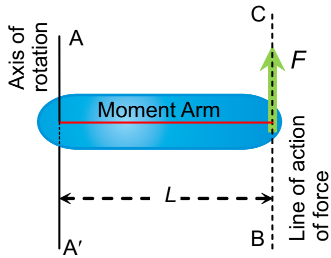


Figure 4.12: Factors affecting the moment of a force.

MOMENT ARM

The perpendicular distance between the axis of rotation and the line of action of the force is called the moment arm of the force. It is represented by the distance **L** in figure 4.12.

The torque or moment of a force depends upon the force **F** and the moment arm *L* of the force. Greater is a force, greater is the moment of the force. Similarly, longer is the moment arm greater is the moment of the force. Thus the moment of the force or torque τ is determined by the product of force *F* and its moment arm *L*. Mathematically,

$$\text{Torque} \quad \tau = F \times L \qquad \dots \quad \dots \quad \dots \quad (4.7)$$

Mini Exercise

A force of 150 N can loosen a nut when applied at the end of a spanner 10 cm long.

1. What should be the length of the spanner to loosen the same nut with a 60 N force?
2. How much force would be sufficient to loosen it with a 6 cm long spanner?

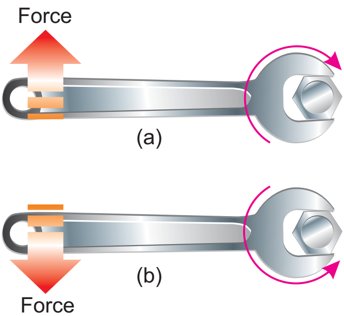


Figure 4.13: (a) to tighten, nut is turned clockwise (b) to loosen, nut is turned anticlockwise.

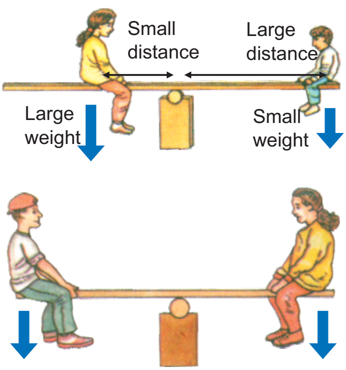


Figure 4.14: Children on see-saw.

SI unit of torque is newton-metre (Nm). A torque of 1 N m is caused by a force of 1 N acting perpendicular to the moment arm 1 m long.

EXAMPLE 4.3

A mechanic tightens the nut of a bicycle using a 15 cm long spanner by exerting a force of 200 N. Find the torque that has tightened it.

SOLUTION

$F = 200$ N

$L = 15$ cm $= 0.15$ m

Using $\tau = F\,L$

$= 200 \text{ N} \times 0.15 \text{ m}$

$= 30$ N m

Thus, a torque of 30 N m is used to tighten the nut.

4.5 PRINCIPLE OF MOMENTS

A force that turns a spanner in the clockwise direction is generally used to tighten a nut as shown in figure 4.13(a). The torque or moment of the force so produced is called clockwise moment. On the other hand, to loosen a nut, the force is applied such that it turns the nut in the anticlockwise direction as shown in figure 4.13(b). The torque or moment of the force so produced is called anticlockwise moment.

A body initially at rest does not rotate if sum of all the clockwise moments acting on it is balanced by the sum of all the anticlockwise moments acting on it. This is known as the principle of moments. According to the principle of moments:

A body is balanced if the sum of clockwise moments acting on the body is equal to the sum of anticlockwise moments acting on it.

QUICK QUIZ

1. Can a small child play with a fat child on the seesaw? Explain how?
2. Two children are sitting on the see-saw, such that they can not swing. What is the net torque in this situation?

EXAMPLE 4.4

A metre rod is supported at its middle point O as shown in figure 4.15. The block of weight 10 N is suspended at point B, 40 cm from O. Find the weight of the block that balances it at point A, 25 cm from O.

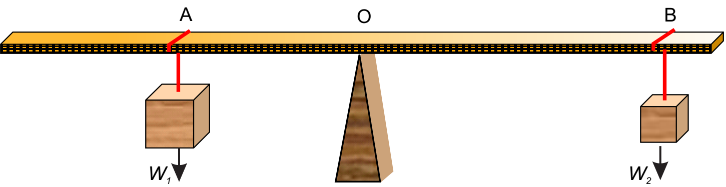


Figure 4.15: Balancing a metre rod on a wedge

SOLUTION

$w_1 = ?$

$w_2 = 10\text{ N}$

Moment arm of w_1 = OA = 25 cm = 0.25 m

Moment arm of w_2 = OB = 40 cm = 0.40 m

Applying principle of moments;

Clockwise moments = Anticlockwise moments

moment of w_2 = moment of w_1

or w_1 x moment arm of w_2 = w_1 x moment arm of w_1

Thus $w_1 \times \text{OA} = w_2 \times \text{OB}$

or $w_1 \times 0.25\text{ m} = 10\text{ N} \times 0.40\text{ m}$

$$w_1 = \frac{10\text{ N} \times 0.40\text{ m}}{0.25\text{ m}}$$

$$= 16\text{ N}$$

Thus, weight of the block suspended at point A is 16 N.

4.6 CENTRE OF MASS

It is observed that the centre of mass of a system moves as if its entire mass is confined at that point. A force applied at such a point in the body does not produce any torque in it i.e. the body moves in the direction of net force *F* without rotation.

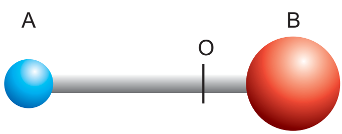


Figure 4.16: Centre of mass of two unequal masses.

Consider a system of two particles A and B connected by a light rigid rod as shown in figure 4.16.

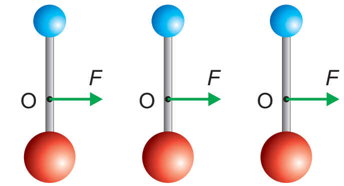


Figure 4.17: A force applied at COM moves the system without rotation.

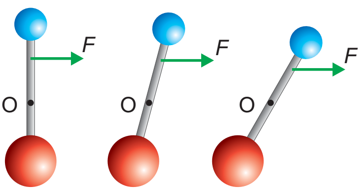


Figure 4.18: The system moves as well as rotates when a force is applied away from COM.

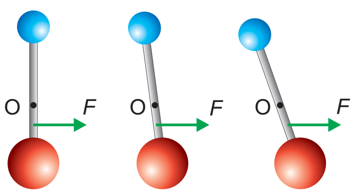


Figure 4.19: The system moves as well as rotates when a force is applied away from COM.

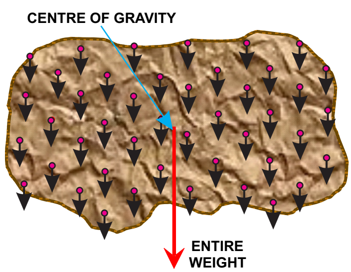


Figure 4.20: Centre of gravity of a body is a point where its entire weight is assumed to act vertically downward.

Let O is a point anywhere between A and B such that the force *F* is applied at point O as shown in figure 4.17. If the system moves in the direction of force *F* without rotation, then point O is the centre of mass of the system.

Does the system still move without rotation if the force acts elsewhere on it?

(i) Let the force be applied near the lighter particle as shown in figure 4.18. The system moves as well as rotates.

(ii) Let the force be applied near the heavier particle as shown in figure 4.19. In this case, also the system moves as well as rotates.

Centre of mass of a system is such a point where an applied force causes the system to move without rotation.

4.6 CENTRE OF GRAVITY

A body is made up of a large number of particles as illustrated in figure 4.20. Earth attracts each of these particles vertically downward towards its centre. The pull of the Earth acting on a particle is equal to its weight. These forces acting on the particles of a body are almost parallel. The resultant of all these parallel forces is a single force equal to the weight of the body. A point where this resultant force acts vertically towards the centre of the Earth is called the centre of gravity G of the body.

A point where the whole weight of the body appears to act vertically downward is called centre of gravity of a body.

It is useful to know the location of the centre of gravity of a body in problems dealing with equilibrium.

CENTRE OF GRAVITY OF SOME SYMMETRICAL OBJECTS

The centre of gravity of objects which have symmetrical shapes can be found from their geometry. For example, the centre of gravity of a uniform rod lies at a point where it is balanced. This balance point is its middle point G as shown in figure 4.21.

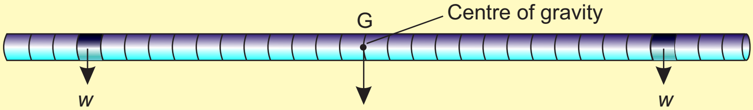


Figure 4.21: Centre of gravity is at the middle of a uniform rod.

The centre of a gravity of a uniform square or a rectangular sheet is the point of intersection of its diagonals as shown in figure 4.22 (a) and (c). The centre of gravity of a uniform circular disc is its centre as shown in figure 4.22(b). Similarly, the centre of gravity of a solid sphere or hollow sphere is the centre of the spheres as shown in figure 4.22(b).

The centre of gravity of a uniform triangular sheet is the point of intersection of its medians as shown in figure 4.22 (d). The centre of gravity of a uniform circular ring is the centre of the ring as shown in figure 4.22(e). The centre of gravity of a uniform solid or hollow cylinder is the middle point on its axis as shown in figure 4.22(f).

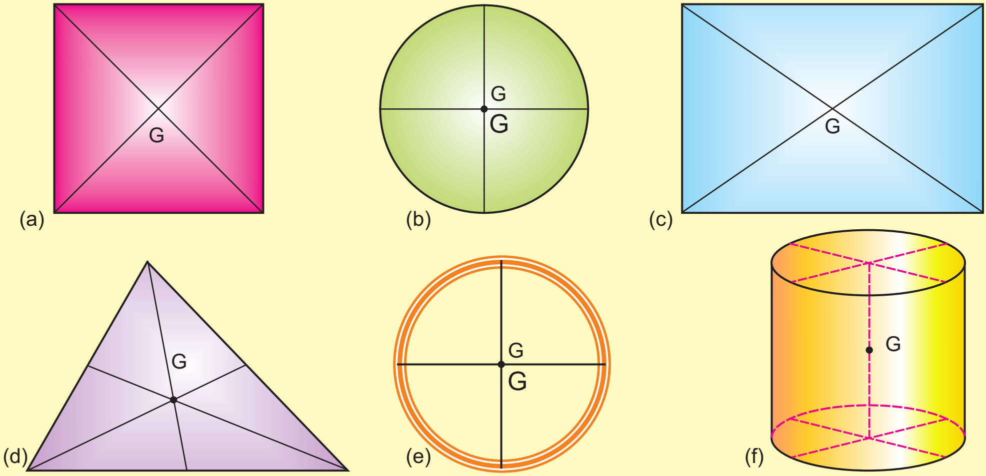


Figure 4.22: Centre of gravity of some symmetrical objects.

CENTRE OF GRAVITY OF AN IRREGULAR SHAPED THIN LAMINA

A simple method to find the centre of gravity of a body is by the use of a plumbline. A plumbline consists of a small metal bob (lead or brass) supported by a string. When the bob is suspended freely by the string, it rests along the vertical direction due to its weight acting vertically downward as shown in figure 4.23 (a). In this state, centre of gravity of the bob is exactly below its point of suspension.

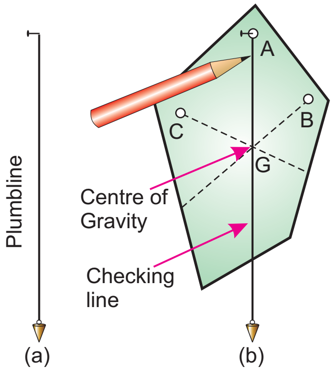


Figure 4.23: (a) Plumbline (b) Locating the centre of gravity of a piece of cardboard by using plumbline.

EXPERIMENT

Take an irregular piece of cardboard. Make holes A, B and C as shown in figure 4.23(b) near its edge. Fix a nail on a wall. Support the cardboard on the nail through one of the holes (let it be A), so that the cardboard can swing freely about A. The cardboard will come to rest with its centre of gravity just vertically below the nail. Vertical line from A can be located using a plumbline hung from the nail. Mark the line on the cardboard behind the plumbline. Repeat it by supporting the cardboard from hole B. The line from B will intersect at a point G. Similarly, draw another line from the hole C. Note that this line also passes through G. It will be found that all the vertical lines from holes A B and C have a common point G. This Common point G is the **centre of gravity** of the cardboard.

4.7 COUPLE

When a driver turns a vehicle, he applies forces that produce a torque. This torque turns the steering wheel. These forces act on opposite sides of the steering wheel as shown in figure 4.24 and are equal in magnitude but opposite in direction. These two forces form a couple.

Figure 4.24: It is easy to turn a steering wheel by applying a couple.

A couple is formed by two unlike parallel forces of the same magnitude but not along the same line.

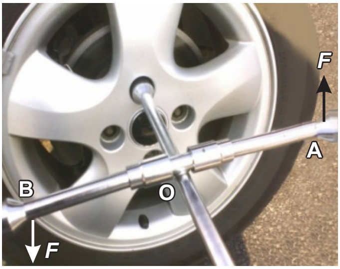


Figure 4.25: A double arm spanner.

A double arm spanner is used to open a nut. Equal forces each of magnitude Fare applied on ends A and B of a spanner in opposite direction as shown in figure 4.25. These forces form a couple that turns the spanner about point O. The torques produced by both the forces of a couple have the same direction. Thus, the total torque produced by the couple will be

Total torque of the couple $= F \times OA + F \times OB$

$= F\,(OA + OB)$

$\therefore$ Torque of the couple $= F \times AB$ ... ... (4.8)

Equation 4.8 gives the torque produced by a couple of forces F and F separated by distance AB. The torque of a couple is given by the product of one of

the two forces and the perpendicular distance between them.

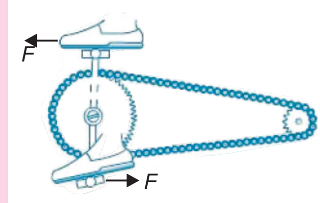
4.8 EQUILIBRIUM

Newton's first law of motion tells us that a body continues its state of rest or of uniform motion in a straight line if no resultant or net force acts on it. For example, a book lying on a table or a picture hanging on a wall, are at rest. The weight of the book acting downward is balanced by the upward reaction of the table. Consider a log of wood of weight w supported by ropes as shown in figure 4.26. Here the weight w is balanced by the forces F_1 and F_2 pulling the log upward. In case of objects moving with uniform velocity, the resultant force acting on them is zero. A car moving with uniform velocity on a levelled road and an aeroplane flying in the air with uniform velocity are the examples of bodies in equilibrium.

A body is said to be in equilibrium if no net force acts on it.

A body in equilibrium thus remains at rest or moves with uniform velocity.

DO YOU KNOW?



A cyclist pushes the pedals of a bicycle. This forms a couple that acts on the pedals. The pedals cause the toothed wheel to turn making the rear wheel of the bicycle to rotate.

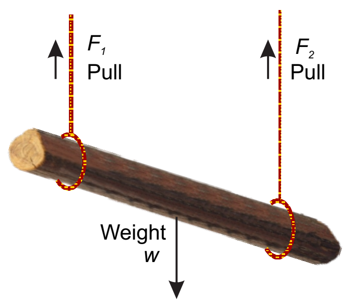


Figure 4.26: The forces acting on the log are; upward forces F_1, F_2 and its weight w in the downward direction.

CONDITIONS FOR EQUILIBRIUM

In the above examples, we see that a body at rest or in uniform motion is in equilibrium if the resultant force acting on it is zero. For a body in equilibrium, it must satisfy certain conditions. There are two conditions for a body to be in equilibrium.

FIRST CONDITION FOR EQUILIBRIUM

A body is said to satisfy first condition for equilibrium if the resultant of all the forces acting on it is zero. Let n number of forces $\mathbf{F_1}, \mathbf{F_2}, \mathbf{F_3}, ..., \mathbf{F_n}$ are acting on a body such that

$$\mathbf{F_1} + \mathbf{F_2} + \mathbf{F_3} + \ldots + \mathbf{F_n} = 0$$

$$\text{or} \qquad \sum \mathbf{F} = 0 \qquad \ldots \quad \ldots \quad \ldots \quad (4.9)$$

The symbol $\sum$ is a Greek letter called sigma used for summation. Equation 4.9 is called the first condition for equilibrium.

Figure 4.27: A wall hanging is in equilibrium

Figure 4.28: A paratrooper coming down with terminal velocity is in equilibrium.

The first condition for equilibrium can also be stated in terms of x and y-components of the forces acting on the body as:

$$F_{1x} + F_{2x} + F_{3x} + \ldots + F_{nx} = 0$$

and $$F_{1y} + F_{2y} + F_{3y} + \ldots + F_{ny} = 0$$

or $$\sum F_x = 0 \quad \ldots \quad \ldots \quad \ldots \quad (4.10)$$

and $$\sum F_y = 0 \quad \ldots \quad \ldots \quad \ldots \quad (4.11)$$

A book lying on a table or a picture hanging on a wall, are at rest and thus satisfy first condition for equilibrium. A paratrooper coming down with terminal velocity (constant velocity) also satisfies first condition for equilibrium and is thus in equilibrium.

EXAMPLE 4.5

A block of weight 10 N is hanging through a cord as shown in figure 4.29. Find the tension in the cord.

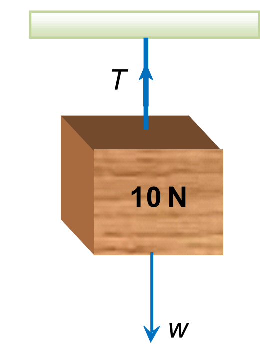


Figure 4.29

SOLUTION

Weight of the block w = 10 N

Tension in the cord T = ?

Applying first condition for equilibrium

$$\sum F_x = 0$$

There is no force acting along x-axis.

$$\sum F_y = 0$$

$$T - w = 0$$

$$T = w$$

$$T = 10\text{ N}$$

Thus, the tension in the cord is 10 N.

SECOND CONDITION FOR EQUILIBRIUM

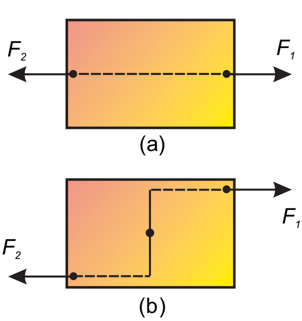


Figure 4.30: (a) Two equal and opposite forces acting along the same lines (b) Two equal and opposite forces acting along different lines

First condition for equilibrium does not ensure that a body is in equilibrium. This is clear from the following example. Consider a body pulled by the forces F_1 and F_2 as shown in figure 4.30(a). The two forces are equal but opposite to each other. Both are acting along the same line, hence their resultant will be zero. According to the first condition, the body will be in

equilibrium. Now shift the location of the forces as shown in figure 4.30(b). In this situation, the body is not in equilibrium although the first condition for equilibrium is still satisfied. It is because the body has the tendency to rotate. This situation demands another condition for equilibrium in addition to the first condition for equilibrium. This is called **second condition for equilibrium.** According to this, a body satisfies second condition for equilibrium when the resultant torque acting on it is zero. Mathematically,

$$\sum \tau = 0 \quad \ldots \ldots \ldots \ldots \ldots \quad (4.12)$$

Figure 4.31: A ladder leaning at a wall.

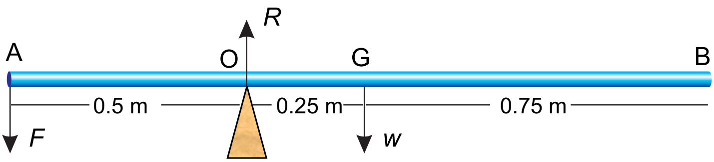
Figure 4.32: A ceiling fan rotating at constant speed is in equilibrium as net torque acting on it is zero.

QUICK QUIZ

1. A ladder leaning at a wall as shown in figure 4.31 is in equilibrium. How?
2. The weight of the ladder in figure 4.31 produces an anticlockwise torque. The wall pushes the ladder at its top end thus produces a clockwise torque. Does the ladder satisfy second condition for equilibrium?
3. Does the speed of a ceiling fan go on increasing all the time?
4. Does the fan satisfy second condition for equilibrium when rotating with uniform speed?

EXAMPLE 4.6

A uniform rod of length 1.5 m is placed over a wedge at 0.5 m from its one end. A force of 100 N is applied at one of its ends near the wedge to keep it horizontal. Find the weight of the rod and the reaction of the wedge.



A rod balanced over a wedge

SOLUTION

$$F = 100\text{ N}$$
$$OA = 0.5\text{ m}$$
$$AG = BG = 0.75\text{ m}$$
$$OG = AG - AO = 0.75\text{ m} - 0.5\text{ m}$$
$$= 0.25\text{ m}$$

$$w = ?$$
$$R = ?$$

Applying second condition for equilibrium, taking torques about O.

$$\sum \tau = 0$$
$$F \times AO + R \times 0 - w \times OG = 0$$
$$100\ \text{N} \times 0.5\ \text{m} - w \times 0.25\ \text{m} = 0$$
$$\text{or} \quad w \times 0.25\ \text{m} = 100\ \text{N} \times 0.5\ \text{m}$$
$$w = \frac{100\,\text{N} \times 0.5\,\text{m}}{0.25\,\text{m}}$$
$$w = 200\ \text{N}$$

Applying first condition for equilibrium

$$\sum F_y = 0$$
$$R - F - w = 0$$
$$R - 100\ \text{N} - 200\ \text{N} = 0$$
$$\text{or} \quad R = 300\ \text{N}$$

Thus, weight of the rod is 200 N and reaction of the wedge is 300 N.

STATES OF EQUILIBRIUM

There are three states of equilibrium; stable equilibrium, unstable equilibrium and neutral equilibrium. A body may be in one of these three states of equilibrium.

STABLE EQUILIBRIUM

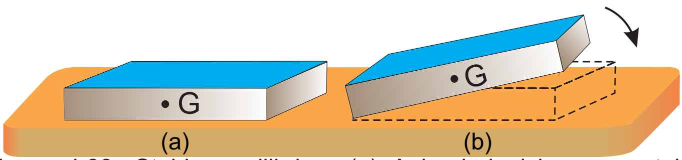


Figure 4.33: Stable equilibrium (a) A book is lying on a table (b) The book returns to its previous position when let free after a slight tilt.

Consider a book lying on the table. Tilt the book slightly about its one edge by lifting it from the opposite side as shown in figure 4.33. It returns to its previous

position when sets free. Such a state of the body is called **stable equilibrium.** Thus

> **A body is said to be in stable equilibrium if after a slight tilt it returns to its previous position.**

When a body is in stable equilibrium, its centre of gravity is at the lowest position. When it is tilted, its centre of gravity rises. It returns to its stable state by lowering its centre of gravity. A body remains in stable equilibrium as long as the centre of gravity acts through the base of the body.

Consider a block as shown in figure 4.34. When the block is tilted, its centre of gravity G rises. If the vertical line through G passes through its base in the tilted position as shown in figure 4.34 (b), the block returns to its previous position. If the vertical line through G gets out of its base as shown in figure 4.34(c), the block does not return to its previous position. It topples over its base and moves to new

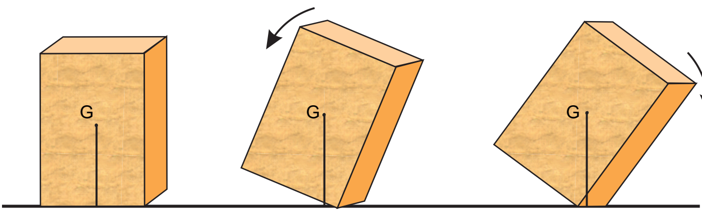


Figure 4.34 (a) Block in stable equilibrium **(b)** Slightly tilted block is returning to its previous position, **(c)** A more tilted block topples over its base and does not return to its previous position.

stable equilibrium position. That is why a vehicle is made heavy at its bottom to keep its centre of gravity as low as possible. A lower centre of gravity keeps it stable. Moreover, the base of a vehicle is made wide so that the vertical line passing through its centre of gravity should not get out of its base during a turn.

UNSTABLE EQUILIBRIUM

Take a pencil and try to keep it in the vertical position on its tip as shown in figure 4.36. Whenever you leave it, the pencil topples over about its tip and falls down. This is called the **unstable equilibrium.** In unstable equilibrium, a body may be made to stay only

Can you do this without falling?

Figure 4.35: A double decker bus being under test for stability.

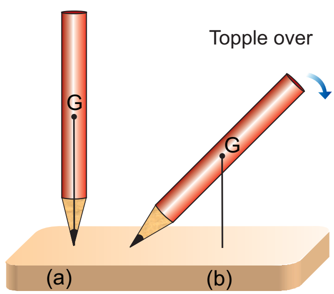


Figure 4.36: Unstable equilibrium
(a) pencil just balanced at its tip with centre of gravity G at the highest position, **(b)** Pencil topples over caused by the torque of its weight acting at G.

DO YOU KNOW?

Vehicles are made heavy at the bottom. This lowers their centre of gravity and helps to increase their stability.

for a moment. Thus a body is unable to keep itself in the state of unstable equilibrium. Thus

If a body does not return to its previous position when sets free after a slightest tilt is said to be in unstable equilibrium.

The centre of gravity of the body is at its highest position in the state of unstable equilibrium. As the body topples over about its base (tip), its centre of gravity moves towards its lower position and does not return to its previous position.

NEUTRAL EQUILIBRIUM

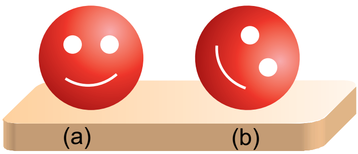


Figure 4.37: Neutral equilibrium (a) a ball is placed on a horizontal surface (b) the ball remains in its new displaced position.

Take a ball and place it on a horizontal surface as shown in figure 4.37. Roll the ball over the surface and leave it after displacing from its previous position. It remains in its new position and does not return to its previous position. This is called neutral equilibrium.

If a body remains in its new position when disturbed from its previous position, it is said to be in a state of neutral equilibrium.

In neutral equilibrium, all the new states in which a body is moved, are the stable states and the body, remains in its new state. In neutral equilibrium, the centre of gravity of the body remains at the same height, irrespective to its new position. There are various objects which have neutral equilibrium such as a ball, a sphere, a roller, a pencil lying horizontally, an egg lying horizontally on a flat surface etc.

4.9 STABILITY AND POSITION OF CENTRE OF MASS

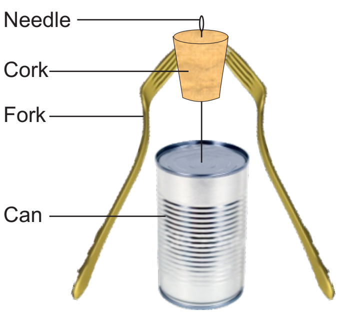


Figure 4.38: A needle is made to balance at its tip.

As we have learnt that position of centre of mass of an object plays an important role in their stability. To make them stable, their centre of mass must be kept as low as possible. It is due to this reason, racing cars are made heavy at the bottom and their height is kept to be minimum. Circus artists such as tight rope walkers use long poles to lower their centre of mass. In this way they are prevented from topple over. Here are few examples in which lowering of centre of mass make the objects stable. These

objects return to their stable states when disturbed. In each case centre of mass is vertically below their point of support. This makes their equilibrium stable.

Figure 4.38 shows a sewing needle fixed in a cork. The cork is balanced on the tip of the needle by hanging forks. The forks lower the centre of mass of the system. Figure 4.39(a) shows a perched parrot which is made heavy at its tail. Figure 4.39(b) shows a toy that keeps itself upright when tilted. It has a heavy semi-spherical base. When it is tilted, its centre of mass rises. It returns to its upright position at which itscentre of mass is at the lowest.

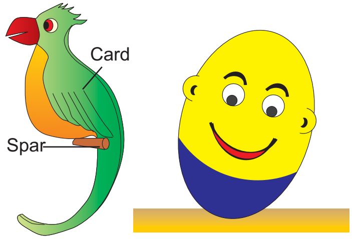


Figure 4.39: (a) A perchd parrot (b) A self righting toy

SUMMARY

- Parallel forces have their lines of action parallel to each other.
- If the direction of parallel forces is the same, they are called like parallel forces. If two parallel forces are in opposite direction to each other, then they are called unlike parallel forces.
- The sum of two or more forces is called the resultant force.
- A graphical method used to find the resultant of two or more forces is called head to tail rule.
- Splitting up a force into two components perpendicular to each other is called resolution of that force. These components are

$$F_x = F\cos\theta, \quad F_y = F\sin\theta$$

- A force can be determined from its perpendicular components as

$$F = \sqrt{F_x^{\,2} + F_y^{\,2}}\ , \quad \theta = \tan^{-1}\frac{F_y}{F_x}$$

- Torque or moment of a force is the turning effect of the force. Torque of a force is equal to the product of force and moment arm of the force.
- According to the principle of moments, the sum of clockwise moments acting on a body in equilibrium is equal to the sum of anticlockwise moments acting on it.
- Centre of mass of a body is such a point where a net force causes it to move without rotation.
- The centre of gravity of a body is a point where the whole weight of a body acts vertically downward.
- A couple is formed by two parallel forces of the same magnitude but acting in opposite direction along different lines of action.
- A body is in equilibrium if net force acting on it is zero. A body in equilibrium either remains at rest or moves with a uniform velocity.
- A body is said to satisfy second condition for equilibrium if the resultant torque acting on it is zero.
- A body is said to be in stable equilibrium if after a slight tilt it returns to its previous position.
- If a body does not return to its previous position when sets free after slightly tilt is said to be in unstable equilibrium.

- A body that remains in its new position when disturbed from its previous position is said to be in a state of neutral equilibrium.

QUESTIONS

4.1 Encircle the correct answers from the given choices:

i. Two equal but unlike parallel forces having different line of action produce
(a) a torque
(b) a couple
(c) equilibrium
(d) neutral equilibrium

ii. The number of forces that can be added by head to tail rule are:
(a) 2 (b) 3
(c) 4 (d) any number

iii. The number of perpendicular components of a force are:
(a) 1 (b) 2
(c) 3 (d) 4

iv. A force of 10 N is making an angle of 30° with the horizontal. Its horizontal component will be :
(a) 4 N (b) 5 N
(c) 7 N (d) 8.7 N

v. A couple is formed by
(a) two forces perpendicular to each other
(b) two like parallel forces
(c) two equal and opposite forces in the same line
(d) two equal and opposite forces not in the same line

vi. A body is in equilibrium when its:
(a) acceleration is uniform
(b) speed is uniform
(c) speed and acceleration are uniform
(d) acceleration is zero

vii. A body is in neutral equilibrium when its centre of gravity:
(a) is at its highest position
(b) is at the lowest position
(c) keeps its height if displaced
(d) is situated at its bottom

viii. Racing cars are made stable by:
(a) increasing their speed
(b) decreasing their mass
(c) lowering their centre of gravity
(d) decreasing their width

4.2 Define the following:
(i) resultant vector
(ii) torque
(iii) centre of mass
(iv) centre of gravity

4.3 Differentiate the following:
(i) like and unlike forces
(ii) torque and couple
(iii) stable and neutral equilibrium

4.4 How head to tail rule helps to find the resultant of forces?

4.5 How can a force be resolved into its perpendicular components?

4.6 When a body is said to be in equilibrium?

4.7 Explain the first condition for equilibrium.

4.8 Why there is a need of second condition for equilibrium if a body satisfies first condition for equilibrium?

4.9 What is second condition for equilibrium?

4.10 Give an example of a moving body which is in equilibrium.

4.11 Think of a body which is at rest but not in equilibrium.

4.12 Why a body cannot be in equilibrium due to single force acting on it?

4.13 Why the height of vehicles is kept as low as possible?

4.14 Explain what is meant by stable, unstable and neutral equilibrium. Give one example in each case.

PROBLEMS

4.1 Find the resultant of the following forces:
(i) 10 N along x-axis
(ii) 6 N along y-axis and
(iii) 4 N along negative x-axis.
(8.5 N making 45° with x-axis)

4.2 Find the perpendicular components of a force of 50 N making an angle of 30° with x axis. (43.3 N, 25 N)

4.3 Find the magnitude and direction of a force, if its x-component is 12 N and y- component is 5 N.
(13 N making 22.6° with x-axis)

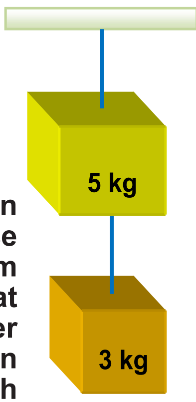
4.4 A force of 100 N is applied perpendicularly on a spanner at a distance of 10 cm from a nut. Find the torque produced by the force. (10 Nm)

4.5 A force is acting on a body making an angle of 30° with the horizontal. The horizontal component of the force is 20 N. Find the force. (23.1 N)

4.6 The steering of a car has a radius 16 cm. Find the torque produced by a couple of 50 N.
(16 Nm)

4.7 A picture frame is hanging by two vertical strings. The tensions in the strings are 3.8 N and 4.4 N. Find the weight of the picture frame. (8.2 N)

4.8 Two blocks of masses 5 kg and 3 kg are suspended by the two strings as shown. Find the tension in each string. (80 N, 30 N)



4.9 A nut has been tightened by a force of 200 N using 10 cm long spanner. What length of a spanner is required to loosen the same nut with 150 N force?
(13.3 cm)

4.10 A block of mass 10 kg is suspended at a distance of 20 cm from the centre of a uniform bar 1 m long. What force is required to balance it at its centre of gravity by applying the force at the other end of the bar? (40 N)

Unit 5

Gravitation

This unit is built on
Gravitation - Science-V
Earth & Space - Science-VI

This unit leads to:
Gravitational Potential,
Escape Velocity and
Artificial Satellite

Major Concepts

5.1 Law of Gravitation

5.2 Measurement of mass of Earth

5.3 Variation of g with altitude

5.4 Motion of artificial satellites

STUDENT'S LEARNING OUTCOMES

After studying this unit, the students will be able to:

- state Newton's law of gravitation.
- explain that the gravitational forces are consistent with Newton's third law.
- explain gravitational field as an example of field of force.
- define weight (as the force on an object due to a gravitational field.)
- calculate the mass of Earth by using law of gravitation.
- solve problems using Newton's law of gravitation.
- explain that value of *g* decreases with altitude from the surface of Earth.
- discuss the importance of Newton's law of gravitation in understanding the motion of satellites.

SCIENCE, TECHNOLOGY AND SOCIETY CONNECTION

The students will be able to:

- gather information to predict the value of the acceleration due to gravity g at any planet or moon's surface using Newton's law of gravitation.
- describe how artificial satellites keep on moving around the Earth due to gravitational force.

The first man who came up with the idea of gravity was Isaac Newton. It was an evening of 1665 when he was trying to solve the mystery why planets revolve around the Sun. Suddenly an apple fell from the tree under which he was sitting. The idea of gravity flashed in his mind. He discovered not only the cause of falling apple but also the cause that makes the planets to revolve around the Sun and the moon around the Earth. This unit deals with the concepts related to gravitation.

5.1 THE FORCE OF GRAVITATION

On the basis of his observations, Newton concluded that the force which causes an apple to fall on the Earth and the force which keeps the moon in its orbit are of the same nature. He further concluded that there exists a force due to which everybody of the universe attracts every other body. He named this force the force of gravitation.

LAW OF GRAVITATION

According to Newton's law of universal gravitation:

Everybody in the universe attracts every other body with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centres.

Consider two bodies of masses m_1 and m_2. The distance between the centres of masses is d as shown in figure 5.1.

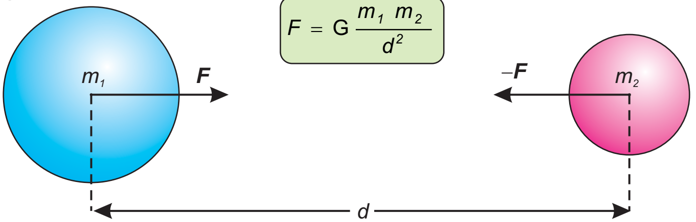


Figure 5.1: Two masses attract each other with a gravitational force of equal magnitude.

According to the law of gravitation, the gravitational force of attraction F with which the two masses m_1 and m_2 separated by a distance d attract each other is given by:

$$F \propto m_1 m_2$$

$$F \propto \frac{1}{d^2}$$

$$\text{or} \qquad F \propto \frac{m_1 m_2}{d^2}$$

$$F = G\frac{m_1 m_2}{d^2} \quad \ldots \ldots \ldots \ldots (5.1)$$

Here G is the proportionality constant. It is called the universal constant of gravitation. Its value is same everywhere. In SI units its value is $6.673 \times 10^{-11}\ Nm^2kg^{-2}$. Due to small value of G, the gravitational force of attraction between objects around us is very small and we do not feel it. Since the mass of Earth is very large, it attracts nearby objects with a significant force. The weight of an object on the Earth is the result of gravitational force of attraction between the Earth and the object.

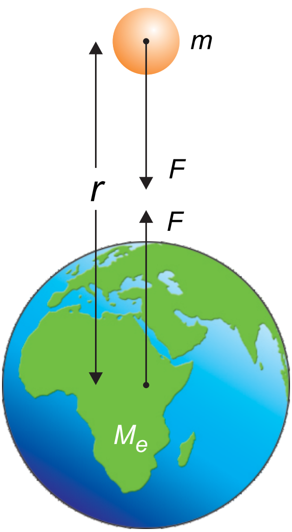


Figure 5.2: Weight of a body is due to the gravitational force between the body and the Earth.

LAW OF GRAVITATION AND NEWTON'S THIRD LAW OF MOTION

It is to be noted that mass m_1 attracts m_2 towards it with a force F while mass m_2 attracts m_1 towards it with a force of the same magnitude F but in opposite direction. If the force acting on m_1 is considered as action then the force acting on m_2 will be the reaction. The action and reaction due to force of gravitation are equal in magnitude but opposite in direction. This is consistent with Newton's third law of motion which states, to every action there is always an equal but opposite reaction.

EXAMPLE 5.1

Two lead spheres each of mass 1000 kg are kept with their centres 1 m apart. Find the gravitational force with which they attract each other.

SOLUTION

Here $m_1 = 1000 \text{ kg}$

$m_2 = 1000 \text{ kg}$

$d = 1 \text{ m}$

Since $F = G\dfrac{m_1 m_2}{d^2}$

Putting the values, we get

$$F = 6.673\times10^{-11}\ \text{Nm}^2\text{kg}^{-2}\times\frac{1000\ \text{kg}\times1000\ \text{kg}}{(1\ \text{m})^2}$$

$$= 6.673\times10^{-5}\ \text{N}$$

Thus, gravitational force of attraction between the lead spheres is 6.673×10^{-5} N.

GRAVITATIONAL FIELD

According to the Newton's law of gravitation, the gravitational force between a body of mass m and the Earth is given by

$$F = G\frac{m M_e}{r^2} \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad (5.2)$$

where M_e is the mass of the Earth and r is the distance of the body from the centre of the Earth.

The weight of a body is due to the gravitational force with which the Earth attracts a body. Gravitational force is a non-contact force. For example, the velocity of a body, thrown up, goes on decreasing while on return its velocity goes on increasing. This is due to the gravitational pull of the Earth acting on the body whether the body is in contact with the Earth or not. Such a force is called the field force. It is assumed that a gravitational field exists all around the Earth. This field is directed towards the centre of the Earth as shown by arrows in figure 5.3. The gravitational field becomes weaker and weaker as we go farther and farther away from the Earth. In the gravitational field of the Earth, the gravitational force per unit mass is called

Figure 5.3: Gravitational field around the Earth is towards its centre.

the **gravitational field strength** of the Earth. At any place its value is equal to the value of g at that point. Near the surface of the Earth, the gravitational field strength is 10 N kg^{-1}.

5.2 MASS OF THE EARTH

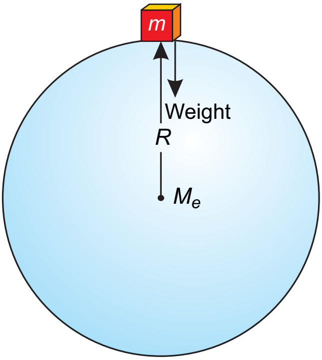


Figure 5.4: Weight of a body is equal to the gravitational force between the body and the Earth.

Consider a body of mass *m* on the surface of the Earth as shown in figure 5.4. Let the mass of the Earth be M_e and radius of the Earth be *R*. The distance of the body from the centre of the Earth will also be equal to the radius *R* of the Earth. According to the law of gravitation, the gravitational force *F* of the Earth acting on a body is given by

$$F = G\frac{mM_e}{R^2} \quad \ldots \ldots \ldots \ldots \ldots \quad (5.3)$$

But the force with which Earth attracts a body towards its centre is equal to its weight w. Therefore,

$$F = w = mg \quad \ldots \ldots \ldots \ldots \ldots \quad (5.4)$$

$$\text{or} \quad mg = G\frac{mM_e}{R^2} \quad \ldots \ldots \ldots \ldots \quad (5.5)$$

$$\therefore \quad g = G\frac{M_e}{R^2} \quad \ldots \ldots \ldots \ldots \quad (5.6)$$

$$\text{and} \quad M_e = \frac{R^2 g}{G} \quad \ldots \ldots \ldots \quad (5.7)$$

Mass M_e of the Earth can be determined on putting the values in equation (5.7).

$$M_e = \frac{(6.4 \times 10^6\ m)^2 \times 10\,m\,s^{-2}}{6.673 \times 10^{-11}\,Nm^2kg^{-2}}$$

$$= 6.0 \times 10^{24}\ kg$$

Thus, mass of the Earth is 6 x 10 kg.

5.3 VARIATION OF G WITH ALTITUDE

Equation (5.6) shows that the value of acceleration due to gravity g depends on the radius of

the Earth at its surface. The value of *g* is inversely proportional to the square of the radius of the Earth. But it does not remain constant. It decreases with **altitude.** Altitude is the height of an object or place above sea level. The value of *g* is greater at sea level than at the hills.

Consider a body of mass *m* at an altitude *h* as shown in figure 5.5. The distance of the body from the centre of the Earth becomes *R* + *h*. Therefore, using equation (5.6), we get

$$g_h = G\frac{M_e}{(R+h)^2} \quad \ldots \ldots \ldots \ldots \quad (5.8)$$

According to the above equation, we come to know that at a height equal to one Earth radius above the surface of the Earth, *g* becomes one fourth of its value on the Earth. Similarly at a distance of two Earths radius above the Earth's surface, the value of *g* becomes one ninth of its value on the Earth.

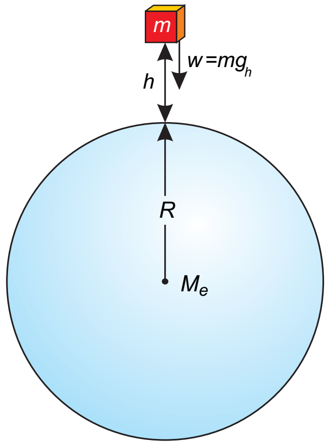


Figure 5.5: Weight of a body decreases as its height increases from the surface of the Earth.

Mini Exercise

1. Does an apple attract the Earth towards it?
2. With what force an apple weighing 1N attracts the Earth?
3. Does the weight of an apple increase, decrease or remain constant when taken to the top of a mountain?

EXAMPLE 5.2

Calculate the value of g, the acceleration due to gravity at an altitude 1000 km. The mass of the Earth is 6.0×10^{24} kg. The radius of the Earth is 6400 km.

SOLUTION

Here $R = 6400$ km

$h = 1000$ km

$M_e = 6.0 \times 10^{24}$ kg

$g_h = ?$

As $R + h = 6400\text{ km} + 1000\text{ km} = 7400$ km

$= 7.4 \times 10^6$ m

$$g_h = G\frac{M_e}{(R+h)^2}$$

$$\therefore \quad g_h = \frac{6.673 \times 10^{-11}\,\text{Nm}^2\,\text{kg}^{-2} \times 6.0 \times 10^{24}\,\text{kg}}{(7.4 \times 10^6\,\text{m})^2}$$

DO YOU KNOW?

Value of *g* on the surface of a celestial object depends on its mass and its radius. The value of *g* on some of the objects is given below:

Object	g (ms^{-2})
Sun	274..2
Mercury	3.7
Venus	8.87
Moon	1.62
Mars	3.73
Jupiter	25.94

$$= 7.3\ \text{N kg}^{-1} = 7.3\ \text{ms}^{-2}$$

Thus the value of g, the acceleration due to gravity at an altitude of 1000 km will be 7.3 ms^{-2}

5.4 ARTIFICIAL SATELLITES

An object that revolves around a planet is called a satellite. The moon revolves around the Earth so moon is a natural satellite of the Earth. Scientists have sent many objects into space. Some of these objects revolve around the Earth. These are called artificial satellites. Most of the artificial satellites, orbiting around the Earth are used for communication purposes. Artificial satellites carry instruments or passengers to perform experiments in space.

DO YOU KNOW?

The height of a geostationary satellite is about 42,300 km from the surface of the Earth. Its velocity with respect to Earth is zero.

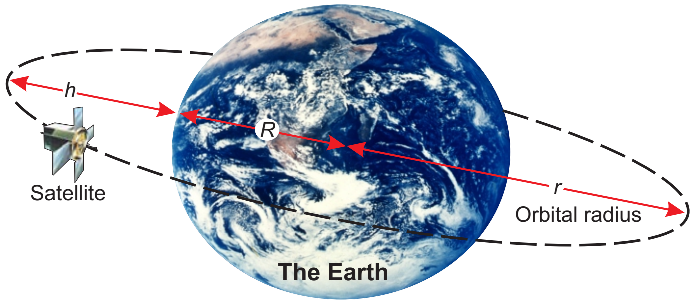


Figure 5.6: A satellite is orbiting around the Earth at a height *h* above the surface of the Earth.

DO YOU KNOW?

Global Positioning System (GPS) is a satellites navigation system. It helps us to find the exact position of an object anywhere on the land, on the sea or in the air. GPS consists of 24 Earth satellites. These satellites revolve around the Earth twice a day with a speed of 3.87 km s^{-1}.

Large number of artificial satellites have been launched in different orbits around the Earth. They take different time to complete their one revolution around the Earth depending upon their distance *h* from the Earth. Communication satellites take 24 hours to complete their one revolution around the Earth. As Earth also completes its one rotation about its axis in 24 hours, hence, these communication satellites appear to be stationary with respect to Earth. It is due to this reason that the orbit of such a satellite is called geostationary orbit. Dish antennas sending and receiving the signals from them have fixed direction depending upon their location on the Earth.

MOTION OF ARTIFICIAL SATELLITES

A satellite requires centripetal force that keeps it to move around the Earth. The gravitational force of attraction between the satellite and the Earth provides the necessary centripetal force.

Consider a satellite of mass *m* revolving round the Earth at an altitude *h* in an orbit of radius r_o with orbital velocity v_o. The necessary centripetal force required is given by equation (3.26).

$$F_c = \frac{mv_o^2}{r_o}$$

This force is provided by the gravitational force of attraction between the Earth and the satellite and is equal to the weight of the satellite w' (mg.). Thus

$$F_c = w' = mg_h \quad \ldots \quad \ldots \quad \ldots \quad (5.9)$$

or $$mg_h = \frac{mv_o^2}{r_o}$$

or $$v_o^2 = g_h\, r_o$$

or $$v_o = \sqrt{g_h\, r_o} \quad \ldots \quad \ldots \quad \ldots \quad (5.10)$$

as $$r_o = R + h$$

$$\therefore \quad v_o = \sqrt{g_h\,(R+h)} \quad \ldots \quad \ldots \quad \ldots (5.11)$$

Equation (5.10) gives the velocity, which a satellite must possess when launched in an orbit of radius $r_o = (R + h)$ around the Earth. An approximation can be made for a satellite revolving close to the Earth such that $R >> h$.

$$R+h = R$$

and $$g_h = g$$

$$\therefore \quad v_o = \sqrt{g\,R} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (5.12)$$

A satellite revolving around very close to the Earth, has speed v_o nearly 8 kms^{-1} or 29000 kmh^{-1}.

DO YOU KNOW?

Moon is nearly 3,80,000 km away from the Earth. It completes its one revolution around the Earth in 27.3 days.

SUMMARY

- Newton's law of universal gravitation states that everybody in the universe attracts every other body with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centres.
- The Earth attracts a body with a force equal to its weight.
- It is assumed that a gravitational field exists all around the Earth due to the gravitational force of attraction of the Earth.
- In the gravitational field of the Earth, the gravitational force per unit mass is called the gravitational field strength of the Earth. It is 10 N kg^{-1} near the surface of the Earth.
- *Acceleration* $g = G\dfrac{M_e}{R^2}$
- Mass of Earth $M_e = \dfrac{R^2 g}{G}$
- g at an altitude $h = G\dfrac{M}{(R+h)^2}$
- An object that revolves around a planet is called a satellite.
- The moon revolves around the Earth so moon is a natural satellite of the Earth.
- Scientists have sent many objects into space. Some of these objects revolve around the Earth. These are called artificial satellites.
- Orbital velocity $v_o = \sqrt{g_h (R+h)}$

QUESTIONS

5.1 Encircle the correct answer from the given choices:

i. Earth's gravitational force of attraction vanishes at

(a) 6400 km (b) infinity

(c) 42300 km (d) 1000 km

ii. Value of g increases with the

(a) increase in mass of the body

(b) increase in altitude

(c) decrease in altitude

(d) none of the above

iii. The value of g at a heightone Earth's radius above the surface of the Earth is:

(a) 2 g (b) ½ g

(c) ⅓ g (d) ¼ g

iv. The value of g on moon's surface is 1.6 ms^{-2} . What will be the weight of a 100 kg body on the surface of the moon?

(a) 100 N (b) 160 N

(c) 1000 N (d) 1600 N

v. The altitude of geostationary orbits in which communication satellites are launched above the surface of the Earth is:

(a) 850 km (b) 1000 km

(c) 6400 km (d) 42,300 km

vi The orbital speed of a low orbit satellite is:

(a) zero (b) 8 ms^{-1}

(c) 800 ms^{-1} (d) 8000 ms^{-1}

5.2 What is meant by the force of gravitation?

5.3 Do you attract the Earth or the Earth attracts you? Which one is attracting with a larger force? You or the Earth.

5.4 What is a field force?

5.5 Why earlier scientists could not guess about the gravitational force?

5.6 How can you say that gravitational force is a field force?

5.7 Explain, what is meant by gravitational field strength?

5.8 Why law of gravitation is important to us?

5.9 Explain the law of gravitation.

5.10 How the mass of Earth can be determined?

5.11 Can you determine the mass of our moon? If yes, then what you need to know?

5.12 Why does the value of *g* vary from place to place?

5.13 Explain how the value of g varies with altitude.

5.14 What are artificial satellites?

5.15 How Newton's law of gravitation helps in understanding the motion of satellites?

5.16 On what factors the orbital speed of a satellite depends?

5.17 Why communication satellites are stationed at geostationary orbits?

PROBLEMS

5.1 Find the gravitational force of attraction between two spheres each of mass 1000 kg. The distance between the centres of the spheres is 0.5 m.

(2.67×10^{-4} N)

5.2 The gravitational force between two identical lead spheres kept at 1 m apart is 0.006673 N. Find their masses.

(10,000 kg each)

5.3 Find the acceleration due to gravity on the surface of the Mars. The mass of Mars is 6.42×10^{23} kg and its radius is 3370 km. **(3.77 ms^{-2})**

5.4 The acceleration due to gravity on the surface of moon is 1.62 ms^{-2}. The radius of moon is 1740 km. Find the mass of moon.

(7.35×10^{22} kg)

5.5 Calculate the value of g at a height of 3600 km above the surface of the Earth. ($4.0\ ms^{-2}$)

5.6 Find the value of g due to the Earth at geostationary satellite. The radius of the geostationary orbit is 48700 km. ($0.17\ ms^{-2}$)

5.7 The value of g is $4.0\ ms^{-2}$ at a distance of 10000 km from the centre of the Earth. Find the mass of the Earth. (5.99×10^{24} kg)

5.8 At what altitude the value of *g* would become one fourth than on the surface of the Earth? (one Earth's radius)

5.9 A polar satellite is launched at 850 km above Earth. Find its orbital speed. ($7431\ ms^{-1}$)

5.10 A communication satellite is launched at 42000 km above Earth. Find its orbital speed. ($2876\ ms^{-1}$)

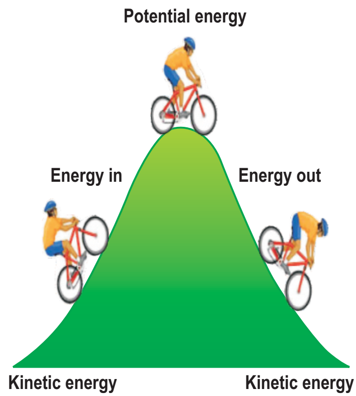
Unit 6

Work and Energy

STUDENT'S LEARNING OUTCOMES

After studying this unit, the students will be able to:

- define work and its SI unit.
- calculate work done using equation
  - Work = force x distance moved in the direction of force
- define energy, kinetic energy and potential energy. State unit of energy.
- prove that kinetic energy K.E. $= \frac{1}{2}mv^2$ and potential energy P.E. = mgh. Solve problems using these equations.
- list the different forms of energy with examples.
- describe the processes by which energy is converted from one form to another with reference to
  - fossil fuel energy
  - hydroelectric generation
  - solar energy
  - nuclear energy
  - geothermal energy
  - wind energy
  - biomass energy
- state mass energy equation $E = mc^2$ and solve problems using it.
- describe the process of electricity generation by drawing a block diagram of the process from fossil fuel input to electricity output.
- list the environmental issues associated with power generation.
- explain by drawing energy flow diagrams through steady state systems such as filament lamp, a power station, a vehicle travelling at a constant speed on a level road.



This unit is built on
Energy - Science-V
Input, output & efficiency - Science-VII

This unit leads to:
Energy & Work - Physics-XI

MAJOR CONCEPTS

6.1 Work

6.2 Energy

6.3 Kinetic energy

6.4 Potential energy

6.5 Forms of energy

6.6 Interconversition of energy

6.7 Major sources of energy

6.8 Efficiency

6.9 Power

- differentiate energy sources as non renewable and renewable energy sources with examples of each.
- define efficiency of a working system and calculate the efficiency of an energy conversion using the formula:

  efficiency = energy output converted into the required form / total energy input
- explain why a system cannot have an efficiency of 100%.
- define power and calculate power from the formula:

  Power = work done / time taken
- define the unit of power "watt" in SI and its conversion with horse power.
- Solve problems using mathematical relations learnt in this unit.

INVESTIGATION SKILLS

The students will be able to:

- investigate conservation of energy of a ball rolling down an inclined plane using double inclined plane and construct a hypothesis to explain the observation.
- compare personal power developed for running upstairs versus walking upstairs using a stopwatch.

SCIENCE, TECHNOLOGY AND SOCIETY CONNECTION

The students will be able to:

- analyse using their or given criteria, the economic , social and environmental impact of various energy sources.[e.g. (fossil fuel, wind, falling water, solar, biomass, nuclear, thermal energy and its transfer(heat)}.
- analyse and explain improvements in sports performance using principles and concepts related to work, kinetic and potential energy and law of conservation of energy (e.g. explain the importance of the initial kinetic energy of a pole vaulter or high jumper).
- search library or internet and compare the efficiencies of energy conversion devices by

comparing energy input and useful energy output.

- explain principle of conservation of energy and apply this principle to explain the conversion of energy from one form to another such as a motor, a dynamo, a photocell and a battery, a freely falling body.
- list the efficient use of energy in the context of the home, heating and cooling of buildings and transportation.

Generally, work refers to perform some task or job. In science, work has precise meaning. For example, a man carrying a load is doing work but he is not doing work if he is not moving while keeping the load on his head. Scientifically, work is done only when an effort or force moves an object. When work is done, energy is used. Thus, work and energy are related to each other. The concept of energy is an important concept in Physics. It helps us to identify the changes that occur when work is done This unit deals with the concepts of work, power and energy.

6.1 WORK

In Physics, work is said to be done when a force acts on a body and moves it in the direction of the force. The question arises how much work is done? Naturally, greater is the force acting on a body and longer is the distance moved by it, larger would be the work done. Mathematically, Work is a product of force F and displacement S in the direction of force. Thus

Work done = Force x displacement

or $$W = FS \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (6.1)$$

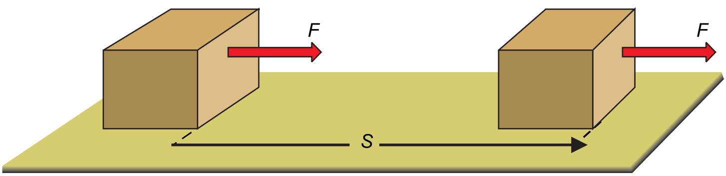


Figure 6.1: Work done in displacing a body in the direction of force.

Sometimes force and displacement do not have the same direction such as shown in figure 6.2. Here the force F is making an angle θ with the surface on which

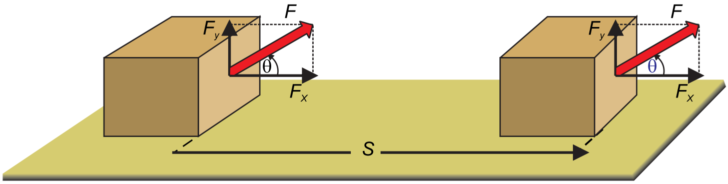


Figure 6.2: Work done by a force inclined with the displacement.

the body is moved. Resolving **F** into its perpendicular components F_x and F_y as;

$$F_x = F\cos\theta$$
$$F_y = F\sin\theta$$

In case when force and displacement are not parallel then only the x-component F_x parallel to the surface causes the body to move on the surface and not the y - component F_y.

Hence $W = F_x S$

$$= (F\cos\theta)\, S$$
$$= F S\cos\theta \quad \ldots \quad \ldots \quad \ldots (6.2)$$

Work is done when a force acting on a body displaces it in the direction of a force.

Work is a scalar quantity. It depends on the force acting on a body, displacement of the body and the angle between them.

UNIT OF WORK

SI unit of work is joule (J). It is defined as

The amount of work is one joule when a force of one newton displaces a body through one metre in the direction of force.

Thus $1\text{ J} = 1\text{ N} \times 1\text{ m}$

Joule is a small unit of work. Its bigger units are:

1 kilo joule (kJ) = 1000 J $= 10^3$ J 1

mega joule (MJ) =1000 000 J $=10^6$ J

Mini Exercise

A crate is moved by pulling the rope attached to it. It moves 10 m on a straight horizontal road by a force of 100 N. How much work will be done if

1. the rope is parallel to the road.
2. the rope is making an angle of 30° with the road.

EXAMPLE 6.1

A girl carries a 10 kg bag upstairs to a height of 18 steps, each 20 cm high. Calculate the amount of work she has done to carry the bag. (Take $g = 10\ ms^{-2}$).

SOLUTION

Mass of the bag $m = 10$ kg

Weight of the bag $w = mg = 10\ kg \times 10\ ms^{-2}$

$= 100$ N

To carry the bag upstairs, the girl exerts an upward force *F* equal to *w*, the weight of the bag. Thus

$$F = 100\ N$$

$$\text{Height } h = 18 \times 0.2\ m = 3.6\ m$$

$$w = F\ h$$

$$= 100 \times 3.6 = 360\ J$$

The girl has done 360 J of work.

6.2 ENERGY

The energy is an important and fundamental concept in science. It links almost all the natural phenomena. When we say that a body has energy, we mean that it has the ability to do work. Water running down the stream has the ability to do work, so it possesses energy. The energy of running water can be used to run water mills or water turbines.

Figure 6.3: Running water possesses energy.

Energy exists in various forms such as mechanical energy, heat energy, light energy, sound energy, electrical energy, chemical energy and nuclear energy etc. Energy can be transformed from one form into another.

A body possesses energy if it is capable to do work.

Mechanical energy possessed by a body is of two types: kinetic energy and potential energy.

6.3 KINETIC ENERGY

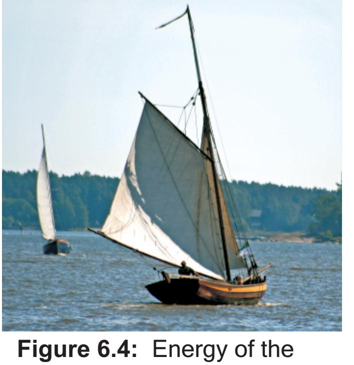


Figure 6.4: Energy of the wind moves the sailing boats.

Moving air is called wind. We can use wind energy for doing various things. It drives windmills and pushes sailing boats. Similarly, moving water in a river can carry wooden logs through large distances and

can also be used to drive turbines for generating electricity. Thus a moving body has kinetic energy, because it can do work due to its motion. The body stops moving as soon as all of its kinetic energy is used up.

The energy possessed by a body due to its motion is called its kinetic energy.

Consider a body of mass *m* moving with velocity *v*. The body stops after moving through some distance *S* due to some opposing force such as force of friction acting on it. The body possesses kinetic energy and is capable to do work against opposing force *F* until all of its kinetic energy is used up.

∴ K.E. of the body = Work done by it due to motion

$$\text{K.E.} = F\,S \quad \ldots \ldots \ldots \quad (6.3)$$

$$v_i = v$$

$$v_f = 0$$

As $$F = ma$$

∴ $$a = -\frac{F}{m}$$

Since motion is opposed, hence, a is negative. Using 3rd equation of motion:

$$2\,a\,S = v_f^{\,2} - v_i^{\,2}$$

$$2\left(-\frac{F}{m}\right)S = (0)^2 - (v)^2$$

$$F\,S = \frac{1}{2}\,m\,v^2 \quad \ldots \ldots \ldots (6.4)$$

From Eq.6.3 and 6.4, we get

$$\text{K.E.} = \frac{1}{2}\,m\,v^2 \quad \ldots \ldots \ldots (6.5)$$

Equation 6.5 gives the K.E possessed by a body of mass *m* moving with velocity *v*.

EXAMPLE 6.2

A stone of mass 500 g strikes the ground with a velocity of 20vms^{-1}. How much is the kinetic energy of the stone at the time it strikes the ground?

SOLUTION

$$m = 500\text{ g} = 0.5\text{ kg}$$

$$v = 20\ \text{ms}^{-1}$$

Since $$\text{K.E.} = \frac{1}{2}mv^2$$

$$\text{K.E.} = \frac{1}{2} \times 0.5\ \text{kg} \times (20\ \text{m s}^{-1})^2$$

$$= \frac{1}{2} \times 0.5\ \text{kg} \times 400\ \text{m}^2\ \text{s}^{-2}$$

$$= 100\ \text{J}$$

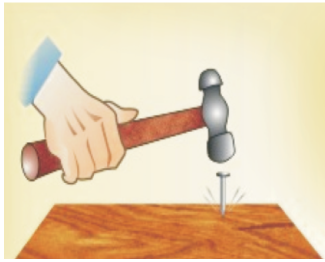
Thus, the kinetic energy of the stone is 100 J as it strikes the ground.

6.4 POTENTIAL ENERGY

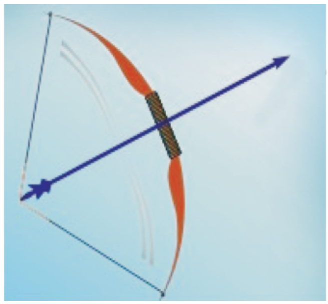
Often a body has the ability to do work although it is at rest. For example, an apple on a tree is capable to do work as it falls. Thus, it possesses energy due to its position. The kind of energy which a body possesses due to its position is called its potential energy.

The energy possessed by a body due to its position is known as its potential energy.

Stored water possesses potential energy due to its height. A hammer raised up to some height has the ability to do work because it possesses potential energy. A stretched bow has potential energy due to its stretched position. When released, the stored energy of the bow pushes the arrow out of it. The energy present in the stretched bow is called elastic potential energy.



(a)



(b)

Figure 6.5: (a) Hammer raised up (b) stretched bow, both possess potential energy.

The potential energy possessed by a hammer is due to its height. The energy present in a body due to its height is called gravitational potential energy.

Let a body of mass *m* be raised up through height *h* from the ground. The body will acquire potential energy equal to the work done in lifting it to height *h.*

Thus Potential energy $\text{P.E.} = F \times h$

$$= w \times h$$

(Here weight of the body $= w = mg$)

$\therefore$ P.E. $= w\,h = m\,g\,h$ ... ... (6.6)

Thus, the potential energy possessed by the body with respect to the ground is *mgh* and is equal to the work done in lifting it to height *h*.

EXAMPLE 6.3

A body of mass 50 kg is raised to a height of 3 m. What is its potential energy? (g = 10 ms^{-2})

SOLUTION

mass m = 50 kg

height h = 3 m

g = 10 ms^{-2}

as P.E. $= m\,g\,h$

$\therefore$ P.E. $= 50\text{ kg} \times 10\text{ m s}^{-2} \times 3\text{ m}$

$= 50 \times 10 \times 3\text{ J}$

$= 1500\text{ J}$

The potential energy of the body is 1500 J.

EXAMPLE 6.4

A force of 200 N acts on a body of mass 20 kg. The force accelerates the body from rest until it attains a velocity of 50 ms^{-1} . Through what distance the force acts?

SOLUTION

Force F = 200 N

Mass m = 20 kg

Velocity v = 50 ms^{-1}

Distance S = ?

Since Work done on the body = K.E. gained by it

$$\therefore \quad F\,S = \frac{1}{2}mv^2$$

$$S = \frac{(20\text{kg})\times(50\text{ms}^{-1})^2}{2\times 200\text{N}} = 125\text{ m}$$

Thus, the distance moved by the body is 125 m.

6.5 FORMS OF ENERGY

Energy exists in various forms. Some of the main forms of energy are given in figure 6.6.

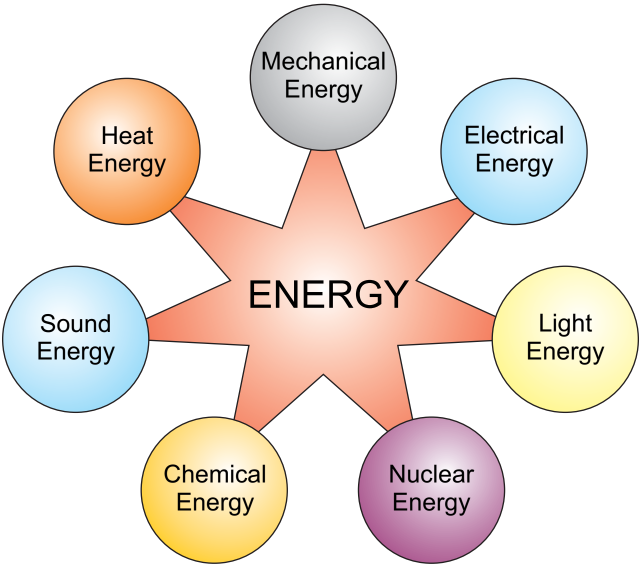


Figure 6.6: Some of the main forms of energy

Figure 6.7: A watermill

MECHANICAL ENERGY

The energy possessed by a body both due to its motion or position is called mechanical energy. Water running down a stream, wind, a moving car, a lifted hammer, a stretched bow, a catapult or a compressed spring etc. possess mechanical energy.

Figure 6.8: Heat energy coming from the Sun.

HEAT ENERGY

Heat is a form of energy given out by hot bodies. Large amount of heat is obtained by burning fuel. Heat is also produced when motion is opposed by frictional forces. The foods we take provide us heat energy. The Sun is the main source of heat energy.

Figure 6.9: Most of the things of our daily use need electrical energy for their operation.

ELECTRICAL ENERGY

Electricity is one of the widely used form of energy. Electrical energy can be supplied easily to any desired place through wires. We get electrical energy from batteries and electric generators. These electric generators are run by hydro power, thermal or nuclear power.

SOUND ENERGY

When you knock at the door, you produce sound. Sound is a form of energy. It is produced when a body vibrates; such as vibrating diaphragm of a drum, vibrating strings of a sitar and vibrating air column of wind instruments such as flute pipe etc.

Figure 6.10: Sound energy

LIGHT ENERGY

Light is an important form of energy. Name some sources of light that you come across.

Figure 6.11: Light is needed during night also.

Plants produce food in the presence of light. We also need light to see things. We get light from candles, electric bulbs, fluorescent tubes and also by burning fuel. However, most of the light comes from the Sun.

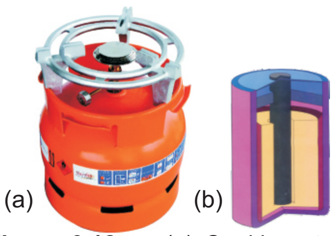


Figure 6.12 (a) Cooking stove with compressed gas cylinder (b) Sectional view of electrical cell.

CHEMICAL ENERGY

Chemical energy is present in food, fuels and in other substances. We get other forms of energy from these substances during chemical reactions. The burning of wood, coal or natural gas in air is a chemical reaction which releases energy as heat and light. Electric energy is obtained from electric cells and batteries as a result of chemical reaction between various substances present in them. Animals get heat and muscular energy from the food they eat.

DO YOU KNOW?

Our body gets energy stored in the food we take to perform various activities.

NUCLEAR ENERGY

Nuclear energy is the energy released in the form of nuclear radiations in addition to heat and light during nuclear reactions such as **fission** and **fusion** reactions. Heat energy released in nuclear reactors is converted into electrical energy. The energy coming from the Sun for the last billions of years is the result of nuclear reactions taking place on the Sun.

DO YOU KNOW?

A nuclear power plant uses the energy released in nuclear reactor such as fission to generate electric power.

6.6 INTERCONVERSION OF ENERGY

Energy cannot be destroyed however it can be converted into some other forms. For example, rub your hands together quickly. You will feel them warm. You have used your muscular energy in rubbing hands as a result heat is produced. In the process of rubbing hands, mechanical energy is converted into heat energy.

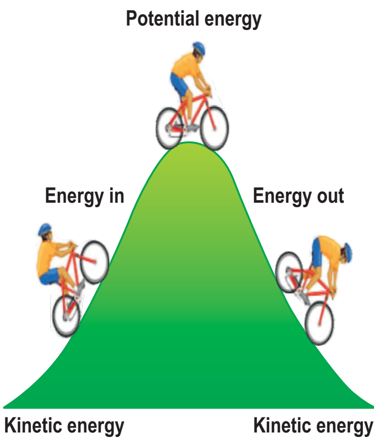


Figure 6.13: Interconversion of kinetic energy into potential energy and potential energy into kinetic energy.

Processes in nature are the results of energy changes. For example, some of the heat energy from the Sun is taken up by water in the oceans. This

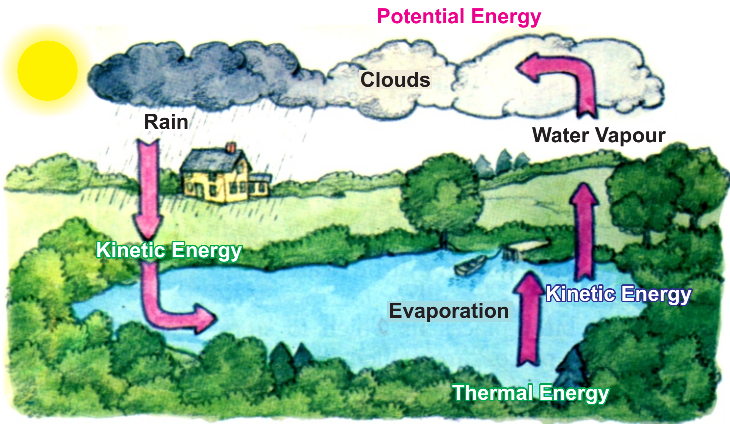


Figure 6.14: Interconversion of Energy

increases the thermal energy. Thermal energy causes water to evaporate from the surface to form water vapours. These vapours rise up and form clouds. As they cool down, they form water drops and fall down as rain. Potential energy changes to kinetic energy as the rain falls This rain water may reach a lake or a dam. As the rain water flows down, its kinetic energy changes into thermal energy while parts of the kinetic energy of flowing water is used to wash away soil particles of rocks known as soil erosion.

DO YOU KNOW?

A pole vaulter uses a flexible vaulting pole made of special material. It is capable to store all the vaulter's kinetic energy while bending in the form of potential energy. The vaulter runs as fast as possible to gain speed. The kinetic energy gained by the pole vaulter due to speed helps him/her to rise up as the vaulter straightens. Thus he attains height as the pole returns the potential energy stored by the vaulter in the pole.

During the interconversion of energy from one form to other forms, the total energy at any time remains constant.

6.7 MAJOR SOURCES OF ENERGY

The energy we use comes from the Sun, wind and water power etc. Actually, all of the energy we get comes directly or indirectly from the Sun.

FOSSIL FUELS

We use fossil fuels such as coal, oil and gas to heat our houses and run industry and transport. They are usually **hydrocarbons** (compounds of carbon and hydrogen). When they are burnt, they combine with oxygen from the air. The carbon becomes carbon

Figure 6.15: A gas field

dioxide; hydrogen becomes hydrogen oxide called water; while energy is released as heat. In case of coal:

Carbon + Oxygen $\rightarrow$ carbon dioxide + heat energy
Hydrocarbon + Oxygen $\rightarrow$ carbon dioxide + water + heat energy

The fossil fuels took millions of years for their formation. They are known as non-renewable resources. We are using fossil fuels at a very fast rate. Their use is increasing day by day to meet our energy needs. If we continue to use them at present rate, they will soon be exhausted. Once their supply is exhausted, the world would face serious energy crisis.

Figure 6.16: Coal

Thus, fossil fuels would not be able to meet our future energy needs. This would cause serious social and economical problems for countries like us. Therefore, we must use them wisely and at the same time develop new energy sources for our future survival.

Figure 6.17: An oil field

Moreover, fossil fuels release harmful waste products. These wastes include carbon mono-oxide and other harmful gases, which pollute the

Figure 6.18: Pollution due to burning of fossil fuel.

environment. This causes serious health problems such as headache, tension, nausea, allergic reactions, irritation of eyes, nose and throat. Long exposure of these harmful gases may cause asthma, lungs cancer, heart diseases and even damage to brain, nerves and other organs of our body.

NUCLEAR FUELS

In nuclear power plants, we get energy as a result of **fission** reaction. During fission reaction, heavy atoms, such as Uranium atoms, split up into smaller parts releasing a large amount of energy. Nuclear power plants give out a lot of nuclear radiations and vast amount of heat. A part of this heat is used to run power plants while lot of heat goes waste into the environment.

Figure 6.19: Nuclear fuel pallets used in nuclear reactors.

RENEWABLE ENERGY SOURCES

Sunlight and water power are the renewable sources of energy. They will not run out like coal, oil and gas.

ENERGY FROM WATER

Energy from water power is very cheap. Dams are being constructed at suitable locations in different parts of the world. Dams serve many purposes. They help to control floods by storing water. The water stored in dams is used for irrigation and also to generate electrical energy without creating much environmental problems.

Figure 6.20: Energy stored in the water of a dam is used to run power plants.

ENERGY FROM THE SUN

Solar energy is the energy coming from the Sun and is used directly and indirectly. Sunlight does not pollute the environment in any way. The sunrays are the ultimate source of life on the Earth. We are dependent on the Sun for all our food and fuels. If we find a suitable method to use a fraction of the solar energy reaching the Earth, then it would be enough to fulfil our energy requirement.

SOLAR HOUSE HEATING

The use of solar energy is not new. However, its use in houses and offices as well as for commercial industrial purposes is quite recent. Complete solar house heating systems are successfully used in areas with a minimum amount of sunshine in winter. A heating system consists of:

- A collector

- A storage device
- A distribution system

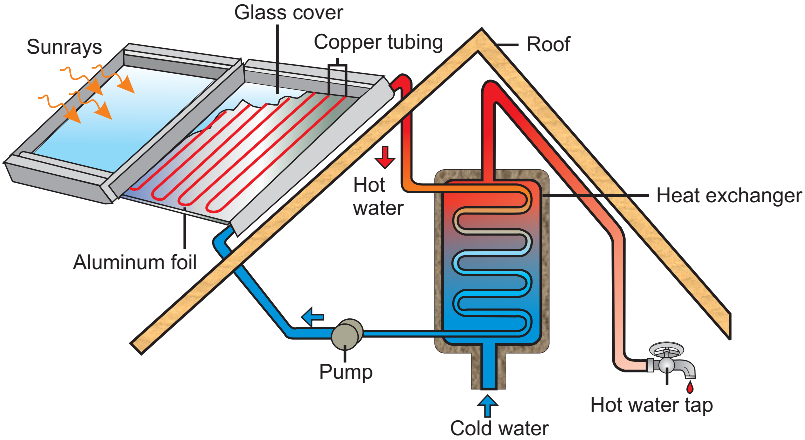


Figure 6.21: A Solar house heating system.

Figure 6.21 shows a solar collector made of glass panels over blank metal plates. The plates absorb the Sun's energy which heats a liquid flowing in the pipes at the back of the collector. The hot water can be used for cooking, washing and heating the buildings.

Solar energy is used in solar cookers, solar distillation plants, solar power plant, etc.

Figure 6.22: A solar car

SOLAR CELLS

Solar energy can also be converted directly into electricity by solar cells. A solar cell also called photo cell is made from silicon wafer. When sunlight falls on a solar cell, it converts the light directly into electrical energy. Solar cells are used in calculators, watches and toys. Large numbers of solar cells are wired together to form solar panels. Solar panels can provide power to telephone booths, light houses and scientific research centres. Solar panels are also used to power satellites.

Figure 6.23: A solar panel fixed at the roof of a house.

Several other methods to trap sunrays are under way. If scientists could find an efficient and inexpensive method to use solar energy, then the people would get clean, limitless energy as long as the Sun continues to shine.

WIND ENERGY

Figure 6.24: Wind turbines

Wind has been used as a source of energy for centuries. It has powered sailing ships across the oceans. It has been used by windmills to grind grain and pump water. More recently, wind power is used to turn wind turbines (Figure 6.24). When many wind machines are grouped together on wind farms, they can generate enough power to operate a power plant. In the United States, some wind farms generate more than 1300 MW of electricity a day. In Europe, many wind farms routinely generate hundred megawatts or more electricity a day.

GEOTHERMAL ENERGY

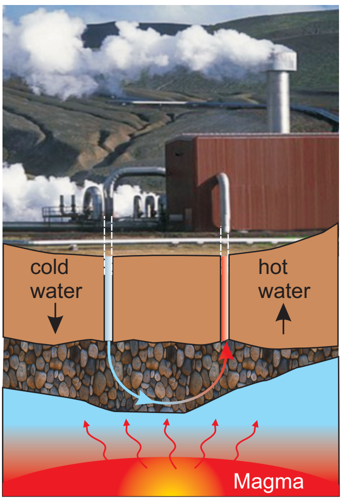


Figure 6.25: A geothermal power station

In some parts of the world, the Earth provides us hot water from geysers and hot springs. There is hot molten part, deep in the Earth called magma. Water reaching close to the magma changes to steam due to the high temperature of magma. This energy is called geothermal energy.

Geothermal well can be built by drilling deep near hot rocks at places, where magma is not very deep. Water is then pushed down into the well. The rocks quickly heat the water and change it into steam. It expands and moves up to the surface. The steam can be piped directly into houses and offices for heating purposes or it can be used to generate electricity.

ENERGY FROM BIOMASS

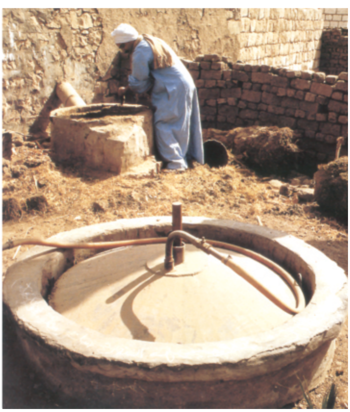


Figure 6.26: A biomass plant using animal dung

Biomass is plant or animal wastes that can be burnt as fuel. Other forms of biomass are garbage, farm wastes, sugarcane and other plants. These wastes are used to run power plants. Many industries that use forest products get half of their electricity by burning bark and other wood wastes. Biomass can serve as another energy source, but problems are there in its use.

When animal dung, dead plants and dead animals decompose, they give off a mixture of methane and carbon dioxide. Electricity can be generated by burning methane.

MASS - ENERGY EQUATION

Einstein predicted the interconversion of matter and energy. According to him, a loss in the mass of a body provides a lot of energy. This happens in nuclear reactions. The relation between mass *m* and energy *E* is given by Einstein's mass-energy equation.

$$E = mc^2 \qquad \ldots\ldots \qquad (6.7)$$

Here *c* is the speed of light ($3 \times 10^8\ ms^{-1}$). The above equation shows that tremendous amount of energy can be obtained from small quantity of matter. It appears that matter is a highly concentrated form of energy. The process of getting energy from our nuclear power plants is based on the above equation. The process is taking place on the Sun and stars for the last millions of years. Only a very small fraction of the Sun's energy reaches the Earth. This very small fraction of the Sun's energy is responsible for life on the Earth.

ELECTRICITY FROM FOSSIL FUELS

We are using electricity in houses, offices, schools, business centres, factories and in farms. We have different ways of generating electricity. Most of the electricity is obtained using fossil fuels such as oil, gas and coal. Fossil fuels are burnt in thermal power stations to produce electricity. Various energy conversion processes involved in producing electricity from coal are described in a block diagram as shown in figure 6.27.

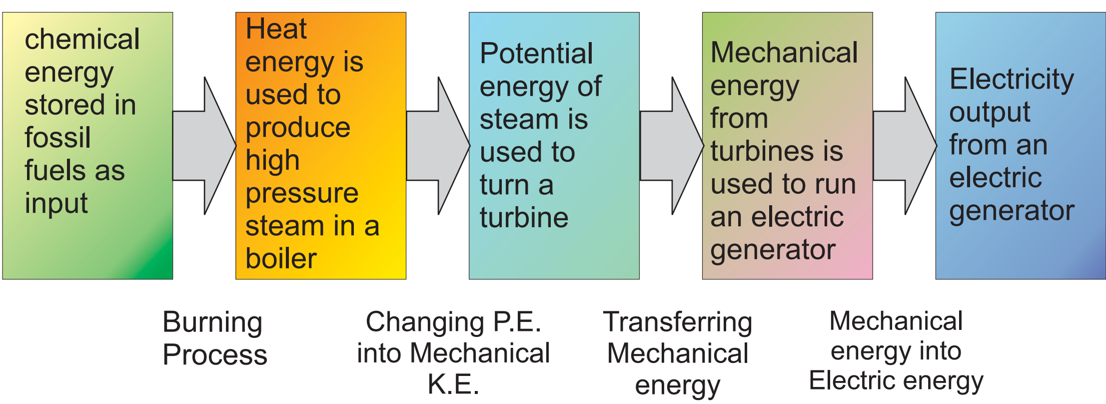


Figure 6.27: Several energy conversion processes are producing electricity.

ENERGY AND ENVIRONMENT

Environmental problems such as pollution that consist of noise, air pollution and water pollution may arise by using different sources of energy such as fossil fuels and nuclear energy. Pollution is the change in the quality of environment that can be harmful and unpleasant for living things. A temperature rise in the environment that disturbs life is called thermal pollution. Thermal pollution upsets the balance of life and endangers the survival of many species.

Air pollutants are unwanted and harmful. Natural processes such as volcanic eruptions, forest fires and dust storms add pollutant to the air. These pollutant, rarely build up to harmful levels. On the other hand, the burning of fuel and solid wastes in homes, automobiles and factories releases harmful amount of air pollutants.

All power plants produce waste heat, but fission plants produce the most. The heat released into a lake, a river or an ocean upsets the balance of life in them. Unlike other power plants, nuclear power plants do not produce carbon dioxide. But they do produce dangerous radioactive wastes.

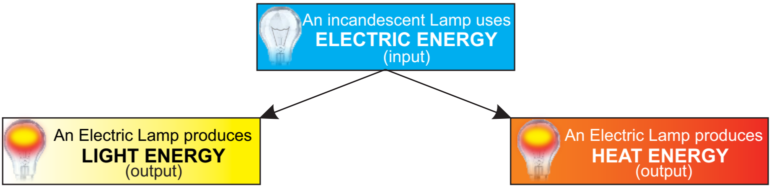
In many countries governments have passed laws to control air pollution. Some of these laws limit the amount of pollution that, power plants, factories and automobiles are allowed to give off. To meet these conditions for automobiles, new cars have catalytic converters. These devices convert some polluting gases. The use of lead free petrol has greatly reduced the amount of lead in the air. Engineers are working to improve new kinds of car engines that use electricity or energy sources other than diesel and petrol.

Many individual communities have laws which protect their areas from pollution. Individuals can help to control air pollution simply by reducing the use of cars and other machines that burn fuel. Sharing rides and using public transportation are the ways to reduce the number of automobiles in use.

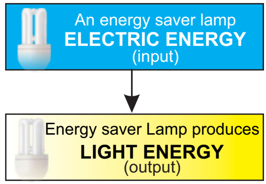
FLOW DIAGRAM OF AN ENERGY CONVERTER

In an energy converter, a part of the energy taken (used up) by the system is converted into useful work. Remaining part of the energy is dissipated as heat energy, sound energy (noise) into the environment. Energy flow diagrams given below show the energy taken up by an energy converter to transform it into other forms of energy.

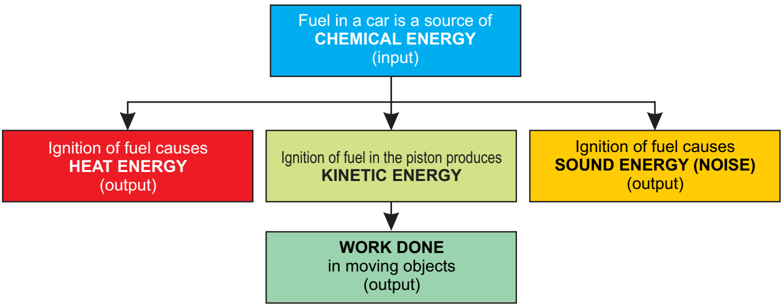
ELECTRIC LAMP



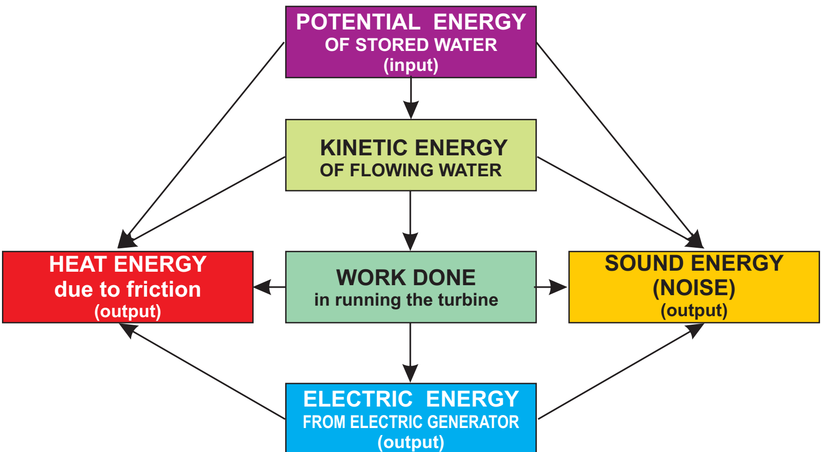
ENERGY SAVER LAMP



VEHICLE RUNNING WITH CONSTANT SPEED ON A LEVEL ROAD



POWER STATION



6.8 EFFICIENCY

Figure 6.28: An electric drill

How to get work done from a machine? We provide some form of energy to a machine. This is necessary for the machine to work. Human machine also needs energy to do a variety of work. We take food to fulfil the energy needs of our body.

We give some form of energy to machines as input to get useful work done by them as output. For example, electric motors may be used to pump water, to blow air, to wash clothes, to drill holes, etc. For that depends how much output we obtain from it by giving certain input. The ratio of useful output to input energy is very important to judge the working of a machine. It is called the efficiency of a machine defined as

Efficiency of a system is the ratio of required form of energy obtained from a system as output to the total energy given to it as input.

For Your Information

Efficiencies of some typical devices/machines

Energy Input	Device or Machine	Useful Work done	% Efficiency
100 J	Electric Lamp	5 J	5 %
100 J	Petrol Engine	25 J	25 %
100 J	Electric Motor	80 J	80 %
100 J	Electric Fan	55 J	55 %
100 J	Solar Cell	3 J	3 %

$$\text{Thus Efficiency} = \frac{\text{required form of output}}{\text{total input energy}} \quad \ldots (6.8)$$

$$\text{or \% Efficiency} = \frac{\text{required form of output}}{\text{total input energy}} \times 100 \quad \ldots (6.9)$$

An ideal system is that which gives an output equal to the total energy used by it. In other words, its efficiency is 100 %. People have tried to design a working system that would be 100 % efficient. But practically such a system does not exist. Every system meets energy losses due to friction that causes heat, noise etc. These are not the useful forms of energy and go waste. This means we cannot utilize all the energy given to a working system. The energy in the required form obtained from a working system is always less than the energy given to it as input.

EXAMPLE 6.5

A cyclist does 12 joules of useful work while pedalling his bike from every 100 joules of food energy which he takes. What is his efficiency?

SOLUTION

Useful work done by the cyclist = 12 J

Energy used by the cyclist = 100 J

$$\text{Efficiency} = \frac{12\text{ J}}{100\text{ J}}$$

$$= 0.12$$

or % efficiency $= 0.12 \times 100 = 12\ \%$

The efficiency of the cyclist is 12 %.

6.9 POWER

Two persons have done equal work, one took one hour to complete it and the other completed it in five hours. No doubt, both of them have done equal work but they differ in the rate at which work is done. One has done it faster than the other. The quantity that tells us the rate of doing work is called power. Thus

Power is defined as the rate of doing work.

Mathematically,

$$\text{Power } P = \frac{\text{Work done}}{\text{Time taken}}$$

$$\text{or} \quad P = \frac{W}{t} \qquad \ldots \ldots (6.10)$$

Since work is a scalar quantity, therefore, power is also a scalar quantity. SI unit of power is **watt** (W). It is defined as

The power of a body is one watt if it does work at the rate of 1 joule per second (1 Js^{-1}).

Bigger units of power are kilowatt (kW), megawatt (MW) etc.

$$1\text{kW} = 1000\text{ W} = 10^3\text{ W}$$

$$1\text{MW} = 1000\ 000\text{ W} = 10^6\text{ W}$$

$$1\text{ horse power} = 1\text{hp} = 746\text{ W}$$

EXAMPLE 6.6

A man takes 80 s in lifting a load of 200 N through a height of 10 m. While another man M_2 takes 10 s in doing the same job. Find the power of each.

SOLUTION

$$F = 200\ \text{N}$$

$$S = 10\ \text{m}$$

Time taken by man $M_1 = t_1 = 80\ \text{s}$

Time taken by man $M_2 = t_2 = 10\ \text{s}$

As work done $= F \times S$

$$= 200\ \text{N} \times 10\ \text{m}$$

$$= 2000\ \text{J}$$

Power of man $M_1 = \dfrac{\text{Work}}{t_1}$

$$= \frac{2000\ \text{J}}{80\ \text{s}} = 25\ \text{Js}^{-1}$$

$$= 25\ \text{watts}$$

and Power of man $= \dfrac{\text{Work}}{t_2}$

$$= \frac{2000\ \text{J}}{10\ \text{s}} = 200\ \text{Js}^{-1}$$

$$= 200\ \text{watts}$$

Thus the power of man M_1 is 25 watts and that of man M_2 is 200 watts.

EXAMPLE 6.7

Calculate the power of a pump which can lift 70 kg of water through a vertical height of 16 metres in 10 seconds. Also find the power in horse power.

SOLUTION

Mass of water $m = 70\ \text{kg}$

Height $S = 16\ \text{m}$

Time taken $t = 10\ \text{s}$

Force required $F = w = m\,g$

$$= 70\ \text{kg} \times 10\ \text{ms}^{-2}$$

$$= 700\ \text{N}$$

Work done $W = F \times S$

or $W = 700\ \text{N} \times 16\ \text{m}$

$$= 11200\ \text{J}$$

$$\text{Power} = \frac{W}{t}$$

$$P = \frac{11200\ \text{J}}{10\ \text{s}} = 1120\ \text{Js}^{-1}$$

$$= 1120\ \text{watts}$$

As $\quad 1\ \text{hp} = 746\ \text{watts}$

$$P = \frac{1120\ \text{watts}}{746\ \text{watts}}\ \text{hp}$$

$$= 1.5\ \text{hp}$$

Thus, power of the pump is 1.5 hp.

SUMMARY

- Work is said to be done when a force acting on a body moves it in the direction of the force.
  - Work $= FS$
  - SI unit of work is joule (J).
- When we say that a body has energy, we mean that it has the ability to do work. SI unit of energy is also joule, the same as work.
- Energy exists in various forms such as mechanical energy, heat energy, light energy, sound energy, electrical energy, chemical energy and nuclear energy etc. Energy from one form can be transformed into another.
- The energy possessed by a body due to its motion is called kinetic energy.
- The energy possessed by a body due to its position is called potential energy.
- Energy cannot be created nor destroyed, but it can be converted from one form to another.
- Processes in nature are the result of energy changes. Heat from the Sun causes water of oceans to evaporate to form clouds. As they cool down, they fall down as rain.
- Einstein predicted the interconversion of matter and energy by the equation $E = mc^2$.
- Fossil fuels are known as non renewable resources because it took millions of years for them to attain the present form.
- Sunlight and water power are the renewable resources of

energy. They will not run out like coal, oil and gas.

- Environmental problems such as polluting emission consisting of noise, air pollution and water pollution may arise by using different sources of energy such as fossil fuels, nuclear energy.
- The ratio of the useful work done by a device or machine to the total energy taken up by it is called its efficiency.
- Power is defined as the rate of doing work.
- The power of a body is one watt which is doing work at the rate of one joule per second.

QUESTIONS

6.1 Encircle the correct answer from the given choices:

i. The work done will be zero when the angle between the force and the distance is

(a) 45° (b) 60°

(c) 90° (d) 180°

ii. If the direction of motion of the force is perpendicular to the direction of motion of the body, then work done will be

(a) Maximum

(b) Minimum

(c) zero

(d) None of the above

iii. If the velocity of a body becomes double, then its kinetic energy will

(a) remain the same

(b) become double

(c) become four times

(d) become half

iv. The work done in lifting a brick of mass 2 kg through a height of 5 m above ground will be

(a) 2.5 J (b) 10 J

(c) 50 J (d) 100 J

v. The kinetic energy of a body of mass 2 kg is 25 J. Its speed is

(a) 5 ms^{-1} (b) 12.5 ms^{-1}

(c) 25 ms^{-1} (d) 50 ms^{-1}

vi. Which one of the following converts light energy into electrical energy?

(a) electric bulb

(b) electric generator

(c) Photocell

(d) Electric cell

vii. When a body is lifted through a height h, the work done on it appears in the form of its:

(a) kinetic energy

(b) potential energy

(c) elastic potential energy

(d) geothermal energy

viii The energy stored in coal is

(a) heat energy

(b) kinetic energy

(c) chemical energy

(d) nuclear energy

ix. The energy stored in a dam is

(a) electric energy

(b) potential energy

(c) kinetic energy

(d) thermal energy

x. In Einstein's mass-energy equation, c is the

(a) speed of sound

(b) speed of light

(c) speed of electron

(d) speed of Earth

xi. Rate of doing work is called

(a) energy (b) torque

(c) power (d) momentum

6.2 Define work. What is its SI unit?

6.3 When does a force do work? Explain.

6.4 Why do we need energy?

6.5 Define energy, give two types of mechanical energy.

6.6 Define K.E. and derive its relation.

6.7 Define potential energy and derive its relation.

6.8 Why fossils fuels are called non-renewable form of energy?

6.9 Which form of energy is most preferred and why?

6.10 How is energy converted from one form to another? Explain.

6.11 Name the five devices that convert electrical energy into mechanical energy.

6.12 Name a device that converts mechanical energy into electrical energy.

6.13 What is meant by the efficiency of a system?

6.14 How can you find the efficiency of a system?

6.15 What is meant by the term power?

6.16 Define watt.

PROBLEMS

6.1 A man has pulled a cart through 35 m applying a force of 300 N. Find the work done by the man. (10500 J)

6.2 A block weighing 20 N is lifted 6 m vertically upward. Calculate the potential energy stored in it. (120 J)

6.3 A car weighing 12 kN has speed of 20 ms^{-1}. Find its kinetic energy. (240 kJ)

6.4 A 500 g stone is thrown up with a velocity of 15ms^{-1}. Find its

(i) P.E. at its maximum height

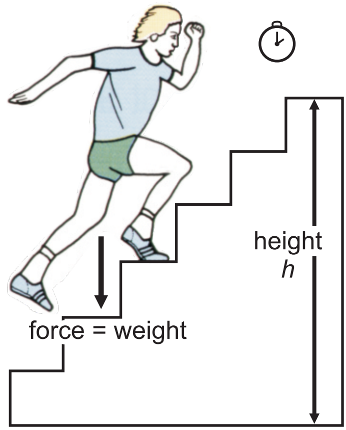
(ii) K.E. when it hits the ground (56.25 J, 56.25 J)

6.5 On reaching the top of a slope 6 m high from its bottom, a cyclist has a speed of 1.5 ms^{-1}. Find the kinetic energy and the potential energy of the cyclist. The mass of the cyclist and his bicycle is 40 kg. (45 J, 2400 J)

6.6 A motor boat moves at a steady speed of 4 ms^{-1}. Water resistance acting on it is 4000 N. Calculate the power of its engine. (16 kW)

6.7 A man pulls a block with a force of 300 N through 50 m in 60 s. Find the power used by him to

6.8 A 50 kg man moved 25 steps up in 20 seconds. Find his power, if each step is 16 cm high. (100 W)



6.9 Calculate the power of a pump which can lift 200 kg of water through a height of 6 m in 10 seconds. (1200 watts)

6.10 An electric motor of 1hp is used to run water pump. The water pump takes 10 minutes to fill an overhead tank. The tank has a capacity of 800 litres and height of 15 m. Find the actual work done by the electric motor to fill the tank. Also find the efficiency of the system.

(Density of water = 1000 kgm^{-3})

(Mass of 1 litre of water = 1 kg)

(447600 J, 26.8 %)

Unit 7

Properties of Matter

STUDENT'S LEARNING OUTCOMES

After studying this unit, the students will be able to:

- state kinetic molecular model of matter (solid, liquid and gas forms).
- describe briefly the fourth state of matter i.e. Plasma.
- define the term density.
- compare the densities of a few solids, liquids and gases.
- define the term pressure (as a force acting normally on unit area).
- explain how pressure varies with force and area in the context of everyday examples.
- explain that the atmosphere exerts a pressure.
- describe how the height of a liquid column may be used to measure the atmospheric pressure.
- describe that atmospheric pressure decreases with the increase in height above the Earth's surface.
- explain that changes in atmospheric pressure in a region may indicate a change in the weather.
- state Pascal's law.
- apply and demonstrate the use with examples of Pascal's law.
- state relation for pressure beneath a liquid surface to depth and to density i.e., (P=ρgh) and solve problems using this equation.

This unit is built on
Matter and its States
- Science -V

This unit leads to:
Fluid Dynamics
- Physics - XI

Physics of Solids
- Physics -XII

- state Archimedes principle.
- determine the density of an object using Archimedes principle.
- state the upthrust exerted by a liquid on a body.
- state principle of floatation.
- explain that a force may produce a change in size and shape of a body.
- define the terms stress, strain and Young's modulus.
- state Hooke's law and explain elastic limit.

Major Concepts

7.1 Kinetic molecular model of matter
7.2 Density
7.3 Pressure
7.4 Atmospheric pressure
7.5 Pressure in liquids
7.6 Upthrust
7.7 Principle of floatation
7.8 Elasticity
7.9 Stress, strain and Young's modulus

INVESTIGATION SKILLS

The students will be able to:

- measure the atmospheric pressure by Fortin's barometer.
- measure the pressure of motor bike / car tyre and state the basic principle of the instrument and its value in SI units.
- determine the density of irregular shaped objects.

SCIENCE, TECHNOLOGY AND SOCIETY CONNECTION

The students will be able to:

- explain that to fix a thumb pin, pressure exerted on the top increases thousands time on the pin point.
- explain the use of Hydrometer to measure the density of a car battery acid.
- explain that ships and submarines float on sea surface when the buoyant force acting on them is greater than their total weight.
- state that Hydraulic Press, Hydraulic car lift and Hydraulic brakes operate on the principle that the fluid pressure is transmitted equally in all directions.

- explain that the action of sucking through a straw, dropper, syringe and vacuum cleaner is due to atmospheric pressure.

Matter exists in three states, solid, liquid and gas. There are many properties associated with matter. For example, matter has weight and occupies space. There are some other properties which are associated with one state of matter but not with other. For example, solids have shape of their own while liquids and gases do not. Liquids on the other hand have definite volume while gases do not have. Various materials differ in their hardness, density, solubility, flow, elasticity, conductivity and many other qualities. Kinetic molecular model helps in understanding the properties of matter in a simplified way.

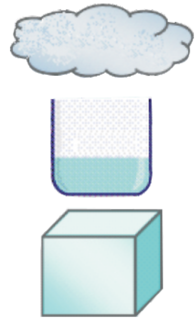


Figure 7.1: Water exists in all the three states.

7.1 KINETIC MOLECULAR MODEL OF MATTER

The kinetic molecular model of matter as shown in figure 7.2 has some important features. These are

- Matter is made up of particles called molecules.
- The molecules remain in continuous motion.
- Molecules attract each other.

Kinetic molecular model is used to explain the three states of matter - solid, liquid and gas.

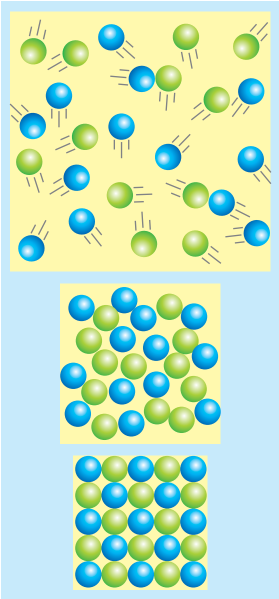


Figure 7.2: Kinetic molecular model of the three states of matter.

SOLIDS

Solids such as a stone, metal spoon, pencil, etc. have fixed shapes and volume. Their molecules are held close together such as shown in figure 7.3 by strong forces of attraction. However, they vibrate about their mean positions but do not move from place to place.

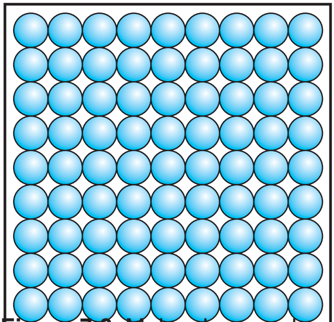


Figure 7.3: Molecules are closely packed in solids.

LIQUIDS

The distances between the molecules of a liquid are more than in solids. Thus, attractive forces

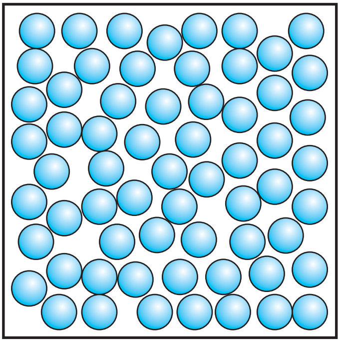


Figure 7.4: Molecules are loosely packed in liquids.

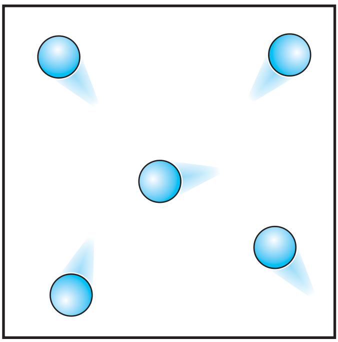


Figure 7.5: Molecules are much farther apart in gases.

Figure 7.6: A plasma bulb

between them are weaker. Like solids, molecules of a liquid also vibrate about their mean position but are not rigidly held with each other. Due to the weaker attractive forces, they can slide over one another. Thus, the liquids can flow. The volume of a certain amount of liquid remains the same but because it can flow hence, it attains the shape of a container to which it is put.

GASES

Gases such as air have no fixed shape or volume. They can be filled in any container of any shape. Their molecules have random motion and move with very high velocities. In gases, molecules are much farther apart than solids or liquids such as shown in figure 7.5. Thus, gases are much lighter than solids and liquids. They can be squeezed into smaller volumes. The molecules of a gas are constantly striking the walls of a container. Thus, a gas exerts pressure on the walls of the container.

PLASMA - THE FOURTH STATE OF MATTER

The kinetic energy of gas molecules goes on increasing if a gas is heated continuously. This causes the gas molecules to move faster and faster. The collisions between atoms and molecules of the gas become so strong that they tear off the atoms. Atoms lose their electrons and become positive ions. This ionic state of matter is called **plasma.** Plasma is also formed in gas discharge tubes when electric current passes through these tubes.

Plasma is called the **fourth state of matter** in which a gas occurs in its ionic state. Positive ions and electrons get separated in the presence of electric or magnetic fields. Plasma also exists in neon and fluorescent tubes when they glow. Most of the matter that fills the universe is in plasma state. In stars such as our Sun, gases exist in their ionic state. Plasma is highly conducting state of matter. It allows electric current to pass through it.

7.2 DENSITY

Is an iron object heavier than that of wood? Not necessary. It depends upon the quantity of iron and wood you are comparing. For example, if we take equal volumes of iron and wood, then we can easily declare that iron is heavier than wood. In other words, we can say that iron is heavier than wood.

To know which substance is denser or which is lighter we generally compare the densities of various substances. The density of a substance is the ratio of its mass to that of its volume. Thus

Density of a substance is defined as its mass per unit volume.

$$\text{Density} = \frac{\text{mass of a substance}}{\text{volume of that substance}} \quad \ldots \quad \ldots \quad (7.1)$$

SI unit of density is kilogramme per cubic metre (kgm^{-3}). We can calculate the density of a material if we know its mass and its volume. For example, the mass of 5 litre of water is 5 kg. Its density can be calculated by putting the values in equation 7.1.

Since $\quad 1 \text{ litre} = 10^{-3} \text{ m}^3$

$\therefore \quad 5 \text{ litre} = 5 \times 10^{-3} \text{ m}^3$

$$\text{Density of water} = \frac{5 \text{ kg}}{5 \times 10^{-3} \text{ m}^3}$$

$$= 1000 \text{ kg m}^{-3}$$

The density of water is 1000 kg m^{-3}.

Table 7.1: Density of various substances

Substance	Density (kgm^{-3})
Air	1.3
Foam	89
Petrol	800
Cooking oil	920
Ice	920
Water	1000
Glass	2500
Aluminium	2700
Iron	7900
Copper	8900
Lead	11200
Mercury	13600
Gold	19300
Platinum	21500

DENSITY EQUATIONS

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

$$\text{Mass} = \text{Density} \times \text{Volume}$$

$$\text{Volume} = \frac{\text{Mass}}{\text{Density}}$$

USEFUL INFORMATION

1 metre cube (1 m^3) = 1000 litre

1 litre = 10^{-3} m^3

1 cm^3 = 10^{-6} m^3

1000 kgm^{-3} = 1 gcm^{-3}

DO YOU KNOW?

Earth's atmosphere extends upward about a few hundred kilometres with continuously decreasing density. Nearly half of its mass is between sea level and 10 km. Up to 30 km from sea level contains about 99% of the mass of the atmosphere. The air becomes thinner and thinner as we go up.

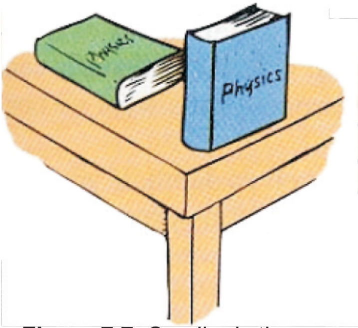


Figure 7.7: Smaller is the area, larger will be the pressure.

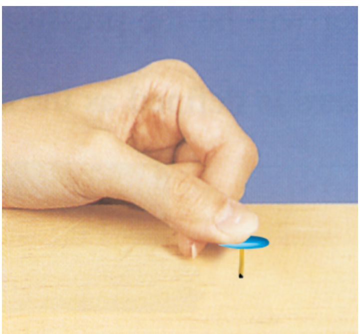


Figure 7.8: A drawing pin with a sharp tip enters easily when pressed on a wooden board.

EXAMPLE 7.1

The mass of 200 cm^3 of stone is 500 g. Find its density.

SOLUTION

$$m = 500\text{g}$$

$$V = 200\text{ cm}^3$$

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

$$= \frac{500\text{ g}}{200\text{ cm}^3} = 2.5\text{ g cm}^{-3}$$

Thus the density of stone is 2.5 g cm^{-3}.

7.3 PRESSURE

Press a pencil from its ends between the palms. The palm pressing the tip feels much more pain than the palm pressing its blunt end. We can push a drawing pin into a wooden board by pressing it by our thumb. It is because the force we apply on the drawing pin is confined just at a very small area under its sharp tip. A drawing pin with a blunt tip would be very difficult to push into the board due to the large area of its tip. In these examples, we find that the effectiveness of a small force is increased if the effective area of the force is reduced. The area of the tip of pencil or that of the nail is very small and hence increases the effectiveness of the force. The quantity that depends upon the force and increases with decrease in the area on which force is acting is called pressure. Thus pressure is defined as

The force acting normally per unit area on the surface of a body is called pressure.

Thus Pressure $P = \dfrac{\text{Force}}{\text{Area}}$

or $$P = \frac{F}{A} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \; (7.2)$$

Pressure is a scalar quantity. In SI units, the unit of pressure is Nm^{-2} also called pascal (Pa). Thus

$$1\ Nm^{-2} = 1\ Pa$$

7.4 ATMOSPHERIC PRESSURE

The Earth is surrounded by a cover of air called atmosphere. It extends to a few hundred kilometres above sea level. Just as certain sea creatures live at the bottom of ocean, we live at the bottom of a huge ocean of air. Air is a mixture of gases. The density of air in the atmosphere is not uniform. It decreases continuously as we go up.

Figure 7.9: The air pressure inside the bubble is equal to the atmospheric pressure.

Atmospheric pressure acts in all directions. Look at the picture in figure 7.9. What the girl is doing? Soap bubbles expand till the pressure of air in them is equal to the atmospheric pressure. Why the soap bubbles so formed have spherical shapes? Can you conclude that the atmospheric pressure acts on a bubble equally in all direction?

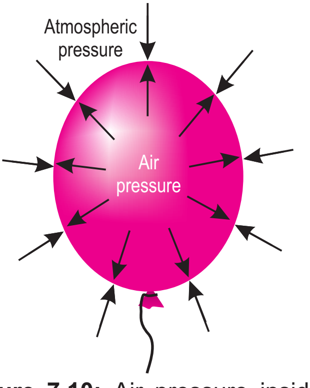


Figure 7.10: Air pressure inside the balloon is equal to the atmospheric pressure.

A balloon expands as we fill air into it. In what direction does the balloon expand? The fact that atmosphere exerts pressure can be explained by a simple experiment.

EXPERIMENT

Take an empty tin can with a lid. Open its cap and put some water in it. Place it over flame. Wait till water begins to boil and the steam expels the air out of the can. Remove it from the flame. Close the can firmly by its cap. Now place the can under tap water. The can will squeeze due to atmospheric pressure. Why?

When the can is cooled by tap water, the steam in it condenses. As the steam changes into water, it leaves an empty space behind it. This lowers the pressure inside the can as compared to the atmospheric pressure outside the can. This will cause the can to collapse from all directions. This experiment shows that atmosphere exerts pressure in all directions.

Figure 7.11: Crushing can experiment.

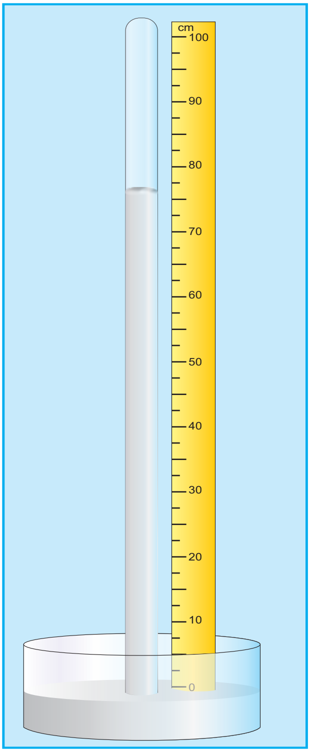


Figure 7.12: A mercury barometer

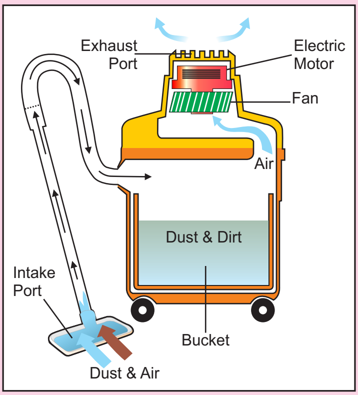
The fact can also be demonstrated by collapsing of an empty plastic bottle when air is sucked out of it.

MEASURING ATMOSPHERIC PRESSURE

At sea level, the atmospheric pressure is about 101,300 Pa or 101,300 Nm^{-2}. The instruments that measure atmospheric pressure are called barometers. One of the simple barometers is a mercury barometer. It consists of a glass tube 1m long closed at one end. After filling it with mercury, it is inverted in a mercury trough. Mercury in the tube descends and stops at a certain height. The column of mercury held in the tube exerts pressure at its base. At sea level the height of mercury column above the mercury in the trough is found to be about 76 cm. Pressure exerted by 76 cm of mercury column is nearly 101,300 Nm^{-2} equal to atmospheric pressure. It is common to express atmospheric pressure in terms of the height of mercury column. As the atmospheric pressure at a place does not remains constant, hence, the height of mercury column also varies with atmospheric pressure.

Mercury is 13.6 times denser than water. Atmospheric pressure can hold vertical column of water about 13.6 times the height of mercury column at a place. Thus, at sea level, vertical height of water column would be 0.76 m x 13.6 = 10.34 m. Thus, a glass tube more than 10 m long is required to make a water barometer.

DO YOU KNOW?



The fan in a vacuum cleaner lowers air pressure in its bucket. The atmospheric air rushes into it carrying dust and dirt with it through its intake port. The dust and dirt particles are blocked by the filter while air escapes out.

VARIATION IN ATMOSPHERIC PRESSURE

The atmospheric pressure decreases as we go up. The atmospheric pressure on mountains is lower than at sea level. At a height of about 30 km, the atmospheric pressure becomes only 7 mm of mercury which is approximately 1000 Pa. It would become zero at an altitude where there is no air. Thus, we can determine the altitude of a place by knowing the atmospheric pressure at that place.

Atmospheric pressure may also indicate a change in the weather. On a hot day, air above the Earth becomes hot and expands. This causes a fall of atmospheric pressure in that region. On the other hand, during cold chilly nights, air above the Earth cools down. This causes an increase in atmospheric pressure.

The changes in atmospheric pressure at a certain place indicate the expected changes in the weather conditions of that place. For example, a gradual and average drop in atmospheric pressure means a low pressure in a neighbouring locality. Minor but rapid fall in atmospheric pressure indicates a windy and showery condition in the nearby region. A decrease in atmospheric pressure is accompanied by breeze and rain. Whereas a sudden fall in atmospheric pressure often followed by a storm, rain and typhoon to occur in few hours time.

On the other hand, an increasing atmospheric pressure with a decline later on predicts an intense weather conditions. A gradual large increase in the atmospheric pressure indicates a long spell of pleasant weather. A rapid increase in atmospheric pressure means that it will soon be followed by a decrease in the atmospheric pressure indicating poor weather ahead.

DO YOU KNOW?

When air is sucked through straw with its other end dipped in a liquid, the air pressure in the straw decreases. This causes the atmospheric pressure to push the liquid up the straw.

7.5 PRESSURE IN LIQUIDS

Liquids exert pressure. The pressure of a liquid acts in all directions. If we take a pressure sensor (a device that measures pressure) inside a liquid, then the pressure of the liquid varies with the depth of sensor.

Consider a surface of area A in a liquid at a depth h as shown by shaded region in figure 7.13. The length of the cylinder of liquid over this surface will be h. The force acting on this surface will be the weight w of the liquid above this surface. If ρ is the density of the liquid and m is mass of liquid above the surface, then

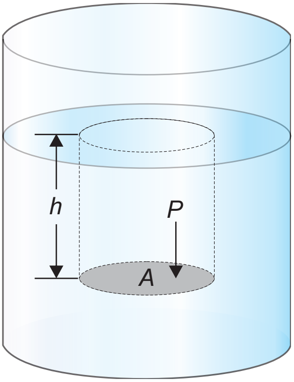


Figure 7.13: Pressure of a liquid at a depth h.

Mass of the liquid cylinder m = volume x density

$$= (A \times h) \times \rho$$

DO YOU KNOW?

The piston of the syringe is pulled out. This lowers the pressure in the cylinder. The liquid from the bottle enters into the piston through the needle.

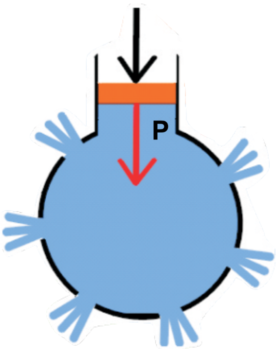


Figure 7.14: Demonstrating Pascal's law.

Figure 7.15 Hydraulic excavator

Force acting on area A $\quad F = w = mg$

$$= Ah\rho g$$

as Pressure $\quad P = \dfrac{F}{A}$

$$= \frac{Ah\rho g}{A}$$

$\therefore$ Liquid pressure at depth h $= P = \rho g h \quad \ldots (7.3)$

Equation (7.3) gives the pressure at a depth h in a liquid of density ρ. It shows that its pressure in a liquid increases with depth.

PASCAL'S LAW

An external force applied on the surface of a liquid increases the liquid pressure at the surface of the liquid. This increase in liquid pressure is transmitted equally in all directions and to the walls of the container in which it is filled. This result is called Pascal's law which is stated as:

Pressure, applied at any point of a liquid enclosed in a container, is transmitted without loss to all other parts of the liquid.

It can be demonstrated with the help of a glass vessel having holes all over its surface as shown in figure 7.14. Fill it with water. Push the piston. The water rushes out of the holes in the vessel with the same pressure. The force applied on the piston exerts pressure on water. This pressure is transmitted equally throughout the liquid in all directions.

In general, this law holds good for fluids both for liquids as well as gases.

APPLICATIONS OF PASCAL'S LAW

Pascal's law finds numerous applications in our daily life such as automobiles, hydraulic brake system, hydraulic jack, hydraulic press and other hydraulic machine such as shown in figure 7.15.

HYDRAULIC PRESS

Hydraulic press is a machine which works on Pascal's law. It consists of two cylinders of different

cross-sectional areas as shown in figure 7.16. They are fitted with pistons of cross-sectional areas *a* and *A*. The object to be compressed is placed over the piston of large cross-sectional area *A*. The force F_1 is applied on the piston of small cross-sectional area a. The pressure *P* produced by small piston is transmitted equally to the large piston and a force F_2 acts on *A* which is much larger than F_1

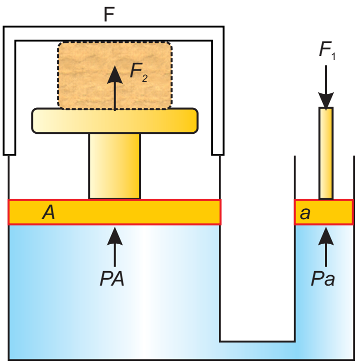


Figure 7.16: A hydraulic press

Pressure on piston of small area *a* is given by

$$P = \frac{F_1}{a}$$

Apply Pascal's law, the pressure on large piston of area *A* will be the same as on small piston.

$$\therefore \quad P = \frac{F_2}{A}$$

Comparing the above equations, we get

$$\frac{F_2}{A} = \frac{F_1}{a}$$

$$\therefore \quad F_2 = A \times \frac{F_1}{a}$$

$$\text{or} \quad F_2 = F_1 \times \frac{A}{a} \quad \text{... ... ... (7.4)}$$

Since the ratio $\frac{A}{a}$ is greater than 1, hence the force F_2 that acts on the larger piston is greater than the force F_1 acting on the smaller piston. Hydraulic systems working in this way are known as force multipliers.

EXAMPLE 7.2

In a hydraulic press, a force of 100 N is applied on the piston of a pump of cross-sectional area 0.01 m^2. Find the force that compresses a cotton bale placed on larger piston of cross-sectional area 1 m^2.

SOLUTION

Here $F_1 = 100N$

$$a = 0.01\ \text{m}^2$$
$$A = 1\ \text{m}^2$$

$$\text{Pressure } P \text{ on smaller piston} = \frac{F_1}{a}$$
$$= \frac{100\ \text{N}}{0.01\ \text{m}^2}$$
$$= 10000\ \text{Nm}^{-2}$$

Applying Pascal's law, we get

$$\text{Force } F_2 \text{ acting on the bale} = PA$$
$$= 10000\ \text{Nm}^{-2} \times 1\text{m}^2$$
$$= 10000\ \text{N}$$

Thus, hydraulic press will compress the bale with a force of 10000 N.

BRAKING SYSTEM IN VEHICLES

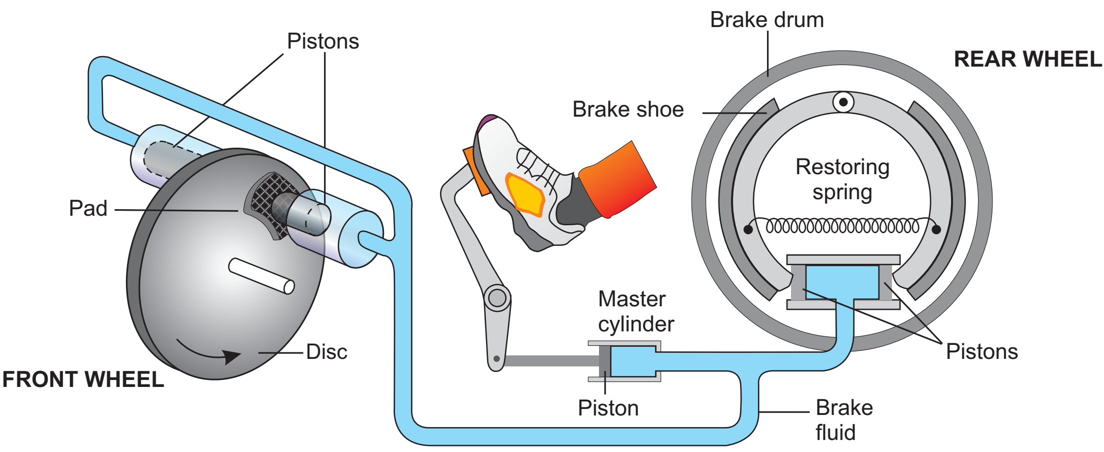


Figure 7.17: A hydraulic brake of a car

The braking systems of cars, buses, etc. also work on Pascal's law. The hydraulic brakes as shown in figure 7.17 allow equal pressure to be transmitted throughout the liquid. When brake pedal is pushed, it exerts a force on the master cylinder, which increases the liquid pressure in it. The liquid pressure is transmitted equally through the liquid in the metal pipes to all the pistons of other cylinders. Due to the increase

in liquid pressure, the pistons in the cylinders move outward pressing the brake pads with the brake drums. The force of friction between the brake pads and the brake drums stops the wheels.

7.6 ARCHIMEDES PRINCIPLE

An air filled balloon immediately shoots up to the surface when released under water. The same would happen if a piece of wood is released under water. We might have noticed that a mug filled with water feels light under water but feels heavy as soon as we take it out of water.

More than two thousand years ago, the Greek scientist, Archimedes noticed that there is an upward force which acts on an object kept inside a liquid. As a result an apparent loss of weight is observed in the object. This upward force acting on the object is called the upthrust of the liquid. Archimedes principle states that:

When an object is totally or partially immersed in a liquid, an upthrust acts on it equal to the weight of the liquid it displaces.

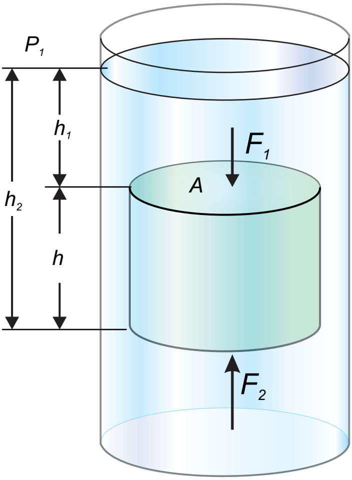


Figure 7.18: Upthrust on a body immersed in a liquid is equal to the weight of the liquid displaced.

Consider a solid cylinder of cross-sectional area A and height h immersed in a liquid as shown in figure 7.18. Let h_1 and h_2 be the depths of the top and bottom faces of the cylinder respectively from the surface of the liquid.

Then $\quad h_2 - h_1 = h$

If P_1 and P_2 are the liquid pressures at depths h_1 and h_2 respectively and ρ is its density, then according to equation (7.3)

$$P_1 = \rho g h_1$$

$$P_2 = \rho g h_2$$

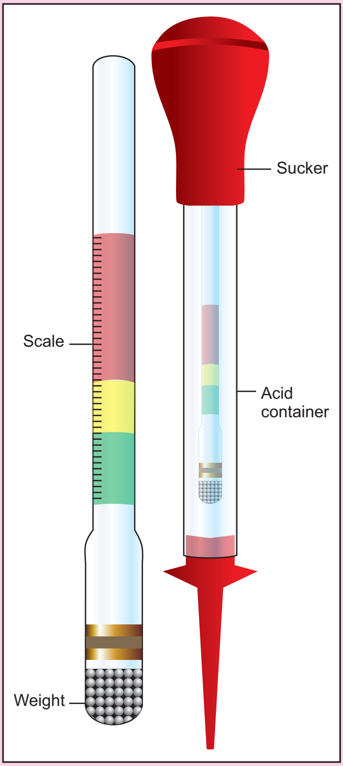
Let the force is exerted at the cylinder top by the liquid due to pressure P_1 and the force F_2 is exerted at the bottom of the cylinder by the liquid due to P_2.

$$\therefore \quad F_1 = P_1 A = \rho\ g\ h_1 A$$

and $$F_2 = P_2 A = \rho\ g\ h_2 A$$

F_1 and F_2 are acting on the opposite faces of the cylinder. Therefore, the net force F will be $F_2 - F_1$ in the direction of F_2. This net force F on the cylinder is called the upthrust of the liquid.

DO YOU KNOW



Hydrometer is a glass tube with a scale marked on its stem and heavy weight in the bottom. It is partially immersed in a fluid, the density of which is to be measured. One type of hydrometer is used to measure the concentration of acid in a battery. It is called acid meter.

$$\therefore \quad F_2 - F_1 = \rho\ g\ h_2 A - \rho\ g\ h_1 A$$

$$= \rho\, g\, A\, (h_2 - h_1)$$

or Upthrust of liquid $= \rho\, g\, A\, h \quad \ldots \quad \ldots \quad (7.5)$

or $= \rho\, g\, V \quad \ldots \quad \ldots \quad (7.6)$

Here Ah is the volume V of the cylinder and is equal to the volume of the liquid displaced by the cylinder. Therefore, $\rho g V$ is the weight of the liquid displaced. Equation (7.6) shows that an upthrust acts on the body immersed in a liquid and is equal to the weight of liquid displaced, which is Archimedes principle.

EXAMPLE 7.3

A wooden cube of sides 10 cm each has been dipped completely in water. Calcuclate the upthurst of water acting on it.

SOLUTION

Length of side $L = 10\text{ cm} = 0.1\text{ m}$

Volume $V = L^3 = (0.1\text{ m})^3 = 1\times 10^{-3}\text{ m}^3$

Density of water $\rho = 1000\text{ kgm}^{-3}$

Upthurst of water $= \rho\ g\ V$

$= 1000\text{ kgm}^{-3} \times 10\text{m s}^{-2} \times 1\times 10^{-3}\text{m}^3$

$= 10\text{ N}$

Thus, upthurst of water acting on the wooden cube is 10 N.

DENSITY OF AN OBJECT

Archimedes principle is also helpful to determine the density of an object. The ratio in the weights of a body with an equal volume of liquid is the same as in their densities.

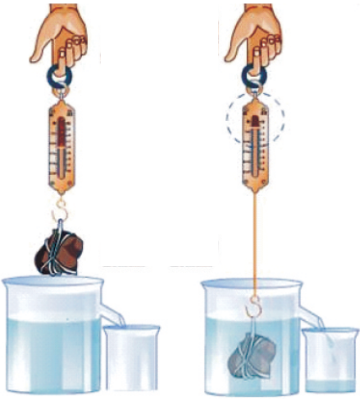
Let Density of the object $= D$

Density of the liquid $= \rho$

Weight of the object $= w_1$

Weight of equal volume of liquid $= w = w_1 - w_2$

Here w_2 is the weight of the solid in liquid. According to Archimedes principle, w_2 is less than its actual weight w_1 by an amount w.



(a) (b)

Figure 7.19: (a) weighing solid in air **(b)** weighing solid in water and measuring water displaced by the solid.

Since $$\frac{D}{\rho} = \frac{w_1}{w}$$

$$D = \frac{w_1}{w} \times \rho$$

or $$D = \frac{w_1}{w_2 - w_1} \times \rho \qquad \dots \dots (7.7)$$

Thus, finding the weight of the solid in air w_1 and its weight in water w_2, we can calculate the density of the solid by using equation 7.7 as illustrated in the following example.

EXAMPLE 7.4

The weight of a metal spoon in air is 0.48 N. its weight in water is 0.42 N. Find its density.

SOLUTION

Weight of the spoon $= 0.48\text{ N}$

Weight of spoon in water $w_2 = 0.42\text{ N}$

Density of water $\rho = 1000\text{ kg m}^{-3}$

Density of spoon $D = ?$

Using equation 7.8,

$$D = \frac{w_1}{w_1 - w_2} \times \rho$$

$$= \frac{0.48\text{N}}{0.48\text{N} - 0.42\text{N}} \times 1000\text{ kg m}^{-3}$$

$$= 8000\text{ kg m}^{-3}$$

Thus, density of the material of the spoon is 8000 kgm^{-3}.

7.7 PRINCIPLE OF FLOATATION

An object sinks if its weight is greater than the upthrust acting on it. An object floats if its weight is equal or less than the upthrust. When an object floats in a fluid, the upthrust acting on it is equal to the weight of the object. In case of floating object, the object may be partially immersed. The upthrust is always equal to the weight of the fluid displaced by the object. This is the principle of floatation. It states that:

A floating object displaces a fluid having weight equal to the weight of the object.

Archimedes principle is applicable on liquids as well as gases. We find numerous applications of this principle in our daily life.

EXAMPLE 7.5

An empty meteorological balloon weighs 80 N. It is filled with 10^3 cubic metres of hydrogen. How much maximum contents the balloon can lift besides its own weight? Th e density of hydrogen is 0.09 kgm $^{-3}$ and the density of air is 1.3 kgm^{-3}.

SOLUTION

Weight of the balloon $w = 80\text{ N}$

Volume of hydrogen $V = 10^3\text{ m}^3$

Density of hydrogen $\rho_1 = 0.09\text{ kg m}^{-3}$

Weight of hydrogen $w_1 = ?$

Density of air $\rho_2 = 1.3\text{ kg m}^{-3}$

Weight of the contents $w_2 = ?$

Upthrust F = Weight of air displaced

$$= \rho_2 V g$$

$$= 1.3\text{ kgm}^{-3} \times 10\text{ m}^3 \times 10\text{ ms}^{-2}$$

$$= 130\text{ N}$$

Weight of hydrogen

$$w_1 = \rho_1 V g$$

$$= 0.09\text{ kgm}^{-3} \times 10\text{ m}^3 \times 10\text{ ms}^{-2}$$

$$= 9\text{ N}$$

Total weight lifted

$$= w + w_1 + w_2$$

To lift the contents, the total weight of the balloon should not exceed F.

$$\begin{aligned}\text{Thus}\quad w + w_1 + w_2 &= F\\ \text{or}\quad 80\text{ N} + 9\text{ N} + w_2 &= 130\text{ N}\\ \text{or}\quad w_2 &= 130\text{ N} - 89\text{ N}\\ &= 41\text{ N}\end{aligned}$$

Thus, the maximum weight of 41 N can be lifted by the balloon in addition to its own weight.

SHIPS AND SUBMARINES

A wooden block floats on water. It is because the weight of an equal volume of water is greater than the weight of the block. According to the principle of floatation, a body floats if it displaces water equal to the weight of the body when it is partially or completely immersed in water.

Figure 7.20: A ship floating over water.

Ships and boats are designed on the same principle of floatation. They carry passengers and goods over water. It would sink in water if its weight including the weight of its passengers and goods becomes greater than the upthrust of water.

A submarine can travel over as well as under water. It also works on the principle of floatation. It floats over water when the weight of water equal to its volume is greater than its weight. Under this condition, it is similar to a ship and remains partially above water level. It has a system of tanks which can be filled with and emptied from seawater. When these tanks are filled with seawater, the weight of the submarine increases. As soon as its weight becomes greater than the upthrust, it dives into water and remains under water. To come up on the surface, the tanks are emptied from seawater.

Figure 7.21: A submarine travels under water.

EXAMPLE 7.6

A barge, 40 metre long and 8 metre broad, whose sides are vertical, floats partially loaded in water. If 125000 N of cargo is added, how many metres will it sink?

SOLUTION

Area of the barge $A = 40\text{ m} \times 8\text{ m}$

$= 320\text{ m}^2$

Additional load w to carry $= 125000\text{ N}$

Increased upthrust F of water must be equal to the additional load. Hence

$$F = \rho V g$$

Since $F = w$

$$\therefore \quad \rho V g = w$$

or $1000\ \text{kg m}^{-3} \times V \times 10\ \text{ms}^{-2} = 125000\ \text{N}$

or $V = 12.5\ \text{m}^3$

Depth h to which barge sinks $= h = \dfrac{V}{A}$

$$\therefore \quad h = \frac{12.5\ \text{m}^3}{320\ \text{m}^2}$$

$$= 0.04\ \text{m} = 4\ \text{cm}$$

Thus, the barge will sink 4 cm in water on adding 125000 N cargo.

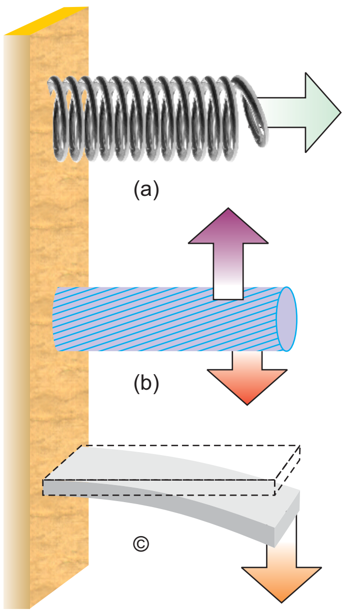


Figure 7.22 (a) A spring is stretched by a force (b) A rod is twisted by the torque produced by a couple (c) A strip is bent by a force.

7.8 ELASTICITY

We know that the length of a rubber band increases on stretching it. Similarly, the pointer of a spring balance is lowered when a body is suspended from it. It is because the length of the spring inside the balance increases depending upon the weight of the suspended body. Look at the pictures in figure 7.22. What happens to the objects due to the forces acting on them. The applied force that changes shape, length or volume of a substance is called deforming force. In most of the cases, the body returns to its original size and shape as soon as the deforming force is removed.

The property of a body to restore its original size and shape as the deforming force ceases to act is called elasticity.

STRESS

Stress is related to the force producing deformation. It is defined as:

The force acting on unit area at the surface of a body is called stress.

Thus $\quad \text{Stress} = \dfrac{\text{Force}}{\text{Area}} \quad \ldots \ldots \ldots \ldots \ldots (7.8)$

In SI, the unit of stress is newton per square metre (Nm^{-2}).

STRAIN

When stress acts on a body, it may change its length, volume, or shape. A ratio of such a change caused by the stress with the original length, volume or shape is called as **strain.** If stress produces a change in the length of an object then the strain is called **tensile strain.**

$$\text{Tensile strain} = \frac{\text{change in length}}{\text{original length}} \quad \ldots \quad \ldots \quad (7.9)$$

Strain has no units as it is simply a ratio between two similar quantities.

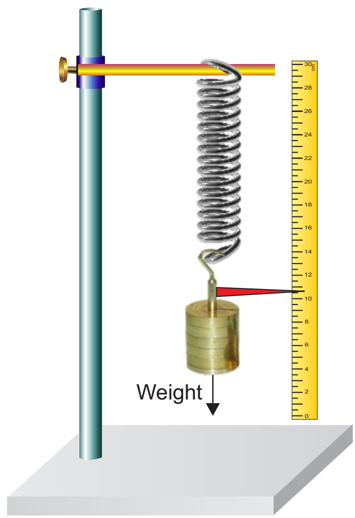


Figure 7.23: Extension in the spring depends upon the load.

7.9 HOOKE'S LAW

It has been observed that deformation in length, volume or shape of a body depends upon the stress acting on the body. Hooke's law states that:

The strain produced in a body by the stress applied to it is directly proportional to the stress within the elastic limit of the body.

Thus $\quad \text{stress} \propto \text{strain}$

or $\quad \text{stress} = \text{constant} \times \text{strain}$

or $$\frac{\text{stress}}{\text{strain}} = \text{constant} \quad \ldots \quad \ldots \quad (7.10)$$

Hooke's law is applicable to all kinds of deformation and all types of matter i.e., solids, liquids or gases within certain limit. This limit tells the maximum stress that can be safely applied on a body without causing permanent deformation in its length, volume or shape. In other words, it is a limit within which a body recovers its original length, volume or shape after the deforming force is removed. When a stress crosses this limit, called the elastic limit, a body is permanently deformed and is unable to restore its original state after the stress is removed.

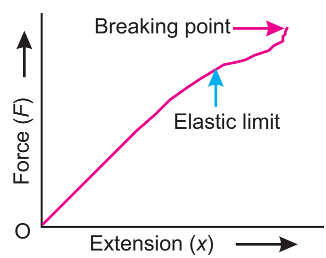


Figure 7.24: Graph between force and extension.

YOUNG'S MODULUS

Consider a long bar of length L_o and cross-sectional area A Let an external force F equal to the weight w stretches it such that the stretched length becomes L. According to Hooke's law, the ratio of this stress to tensile strain is constant within the elastic limit of the body.

The ratio of stress to tensile strain is called Young's modulus.

Mathematically,

$$\text{Young's modulus } Y = \frac{\text{Stress}}{\text{Tensile strain}} \quad \dots \dots (7.11)$$

Let ΔL be the change in length of the rod, then

$$\Delta L = L - L_o$$

Since $$\text{Stress} = \frac{\text{Force}}{\text{Area}} = \frac{F}{A}$$

and $$\text{Tensile strain} = \frac{L - L_o}{L_o} = \frac{\Delta L}{L_o}$$

As $$Y = \frac{\text{Stress}}{\text{Tensile strain}}$$

$$= \frac{F}{A} \times \frac{L_o}{\Delta L}$$

$$\therefore \quad Y = \frac{F\,L_o}{A\,\Delta L} \quad \dots \dots (7.12)$$

SI unit of Young's modulus is newton per square metre (Nm^{-2}) Young's modului of some common materials are given in Table 7.2.

Table 7.2: Young's modului of some common materials

Material	Young's modulus $\times 10^9$ Nm^{-2}
Aluminium	70
Bone	0.02
Brass	91
Copper	110
Diamond	1120
Glass	60
Iron	190
Lead	16
Nickel	200
Rubber	0.0007
Steel	200
Tungsten	400
Wood (parallel gain)	10
Wood (perpendicular gain)	1

EXAMPLE 7.7

A steel wire 1 m long and cross-sectional area 5×10^{-5} m^2 is stretched through 1 mm by a force of 10,000 N. Find the Young's modulus of the wire.

SOLUTION

Force $F = 10{,}000$ N

Length $L_o = 1$m

Extension $\Delta L = 1\text{mm} = 0.001\text{m}$

Cross sectional Area $A = 5 \times 10^{-5}$ m^2

Since
$$Y = \frac{F\,L_o}{A\,\Delta L}$$
$$Y = \frac{10000\ \mathrm{N}\times 1\ \mathrm{m}}{5\times 10^{-5}\ \mathrm{m}^2\times 0.001\ \mathrm{m}}$$
$$Y = 2\times 10^{11}\ \mathrm{N\,m}^{-2}$$

Thus, Young's modulus of steel is 2×10^{11} Nm^{-2}.

SUMMARY

- Kinetic molecular model explains the three states of matter assuming that
  - matter is made up of particles called molecules.
  - the molecules remain in continuous motion.
  - molecules attract each other.
- At very high temperature, the collision between atoms and molecules tears off their electrons. Atoms become positive ions. This ionic state of matter is called plasma-the fourth state of matter.
- Density is the ratio of mass to volume of a substance. Density of water is 1000 kgm^{-3}.
- Pressure is the normal force acting per unit area. Its SI unit is Nm^{-2} or pascal (Pa).
- Atmospheric pressure acts in all directions.
- The instruments that measure atmospheric pressure are called barometers.
- The atmospheric pressure decreases as we go up. Thus, knowing the atmospheric pressure of a place, we can determine its altitude.
- The changes in atmospheric pressure at a certain place indicate the expected changes in the weather conditions of that place.
- Liquids also exert pressure given by: $P = \rho g h$
- Liquids transmit pressure equally in all directions. This is called Pascal's law.
- When a body is immersed wholly or partially in a liquid, it loses its weight equal to the weight of the liquid displaced. This is known as Archimedes principle.
- For an object to float, its weight must be equal or less than the upthrust of the liquid acting on it.
- The property of matter by virtue of which matter resists any force which tries to change its length, shape or volume is called elasticity.
- Stress is the deforming force acting per unit area.
- The ratio of change of length to the original length is called tensile strain.
- The ratio between stress and tensile strain is called Young's modulus.

QUESTIONS

7.1 Encircle the correct answer from the given choices:

i. In which of the following state molecules do not leave their position?

(a) solid (b) liquid

(c) gas (d) plasma

ii. Which of the substances is the lightest one?

(a) copper (b) mercury

(c) aluminum (d) lead

iii. SI unit of pressure is pascal, which is equal to:

(a) 10^4 Nm^{-2} (b) 1 Nm^{-2}

(C)10^2Nm^{-2} (d)10^3Nm^{-2}

iv. What should be the approximate length of a glass tube to construct a water barometer?

(a) 0.5 m (b) 1 m

(c) 2.5 m (d) 11 m

v. According to Archimedes, upthrust is equal to:

(a) weight of displaced liquid

(b) volume of displaced liquid

(c) mass of displaced liquid

(d) none of these

vi. The density of a substance can be found with the help of:

(a)Pascal's law

(b) Hooke's law

(c) Archimedes principle

(d) Principle of floatation

vii. According to Hooke's law

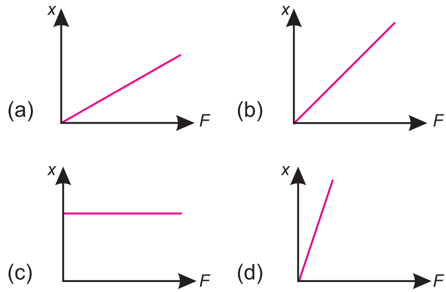
(a) stress x strain = constant

(b) stress / strain = constant

(c) strain / stress = constant

(d) stress = strain

The following force-extension graphs of a spring are drawn on the same scale. Answer the questions given below from (viii) to (x).



viii. Which graph does not obey Hooke's law?

(a) (b) (c) (d)

ix. Which graph gives the smallest value of spring constant?

(a) (b) (c) (d)

x. Which graph gives the largest value of spring constant?

(a) (b) (c) (d)

7.2 How kinetic molecular model of matter is helpful in differentiating various states of matter?

7.3 Does there exist a fourth state of matter? What is that?

7.4 What is meant by density? What is its SI unit?

7.5 Can we use a hydrometer to measure the density of milk?

7.6 Define the term pressure.

7.7 Show that atmosphere exerts pressure.

7.8 It is easy to remove air from a balloon but it is very difficult to remove air from a glass bottle. Why?

7.9 What is a barometer?

7.10 Why water is not suitable to be used in a barometer?

7.11 What makes a sucker pressed on a smooth wall sticks to it?

Suction cup to hang light objects

7.12 Why does the atmospheric pressure vary with height?

7.13 What does it mean when the atmospheric pressure at a place fall suddenly?

7.14 What changes are expected in weather if the barometer reading shows a sudden increase?

7.15 State Pascal's law.

7.16 Explain the working of hydraulic press.

7.17 What is meant by elasticity?

7.18 State Archimedes principle.

7.19 What is upthrust? Explain the principle of floatation.

7.20 Explain how a submarine moves up the water surface and down into water.

7.21 Why does a piece of stone sink in water but a ship with a huge weight floats?

7.22 What is Hooke's law? What is meant by elastic limit?

7.23 Take a rubber band. Construct a balance of your own using a rubber band. Check its accuracy by weighing various objects.

PROBLEMS

7.1 A wooden block measuring 40 cm x 10 cm x 5 cm has a mass 850 g. Find the density of wood. (425 kgm^{3})

7.2 How much would be the volume of ice formed by freezing 1 litre of water? (1.09 litre)

7.3 Calculate the volume of the following objects:

(i) An iron sphere of mass 5 kg, the density of iron is 8200 kgm^{-3}.

(6.1x$10^{-4}m^{3}$)

(ii) 200 g of lead shot having density 11300 kgm^{-3}.

(1.77x$10^{-5}m^{3}$)

(iii) A gold bar of mass 0.2 kg. The density of gold is 19300 kgm^{-3}. ($1.04x10^{-5}m^3$)

7.4 The density of air is 1.3 kgm^{-3}. Find the mass of air in a room measuring 8m x 5m x 4m.
(208 kg)

7.5 A student presses her palm by her thumb with a force of 75 N. How much would be the pressure under her thumb having contact area 1.5 cm^2?
($5x10^5$ Nm^{-2})

7.6 The head of a pin is a square of side 10 mm. Find the pressure on it due to a force of 20 N.
($2x10^5$ Nm^{-2})

7.7 A uniform rectangular block of wood 20 cm x 7.5 cm x 7.5 cm and of mass 1000g stands on a horizontal surface with its longest edge vertical. Find (i) the pressure exerted by the block on the surface (ii) density of the wood.
(1778 Nm^{-2}, 889 kgm^{-3})

7.8 A cube of glass of 5 cm side and mass 306 g, has a cavity inside it. If the density of glass is 2.55 gcm^{-3} . Find the volume of the cavity.
(5 cm^3)

7.9 An object has weight 18 N in air. Its weight is found to be 11.4 N when immersed in water. Calculate its density. Can you guess the material of the object?
(2727 kgm^{-3}, Aluminium)

7.10 A solid block of wood of density 0.6 gcm^{-3} weighs 3.06 N in air. Determine (a) volume of the block (b) the volume of the block immersed when placed freely in a liquid of density 0.9 gcm^{-3}?
(510 cm^3, 340 cm^3)

7.11 The diameter of the piston of a hydraulic press is 30 cm. How much force is required to lift a car weighing 20 000 N on its piston if the diameter of the piston of the pump is 3 cm? (200 N)

7.12 A steel wire of cross-sectional area $2x10^{-5}$ m^2 is stretched through 2 mm by a force of 4000 N. Find the Young's modulus of the wire. The length of the wire is 2 m.
($2x10^{11}Nm^{-2}$)

Unit 8

Thermal Properties of Matter

STUDENT'S LEARNING OUTCOMES

After studying this unit, the students will be able to:

- define temperature (as quantity which determines the direction of flow of thermal energy).
- define heat (as the energy transferred resulting from the temperature difference between two objects).
- list basic thermometric properties for a material to construct a thermometer.
- convert the temperature from one scale to another (Fahrenheit, Celsius and Kelvin scales).
- describe rise in temperature of a body in terms of an increase in its internal energy.
- define the terms heat capacity and specific heat capacity.
- describe heat of fusion and heat of vaporization (as energy transfer without a change of temperature for change of state).
- describe experiments to determine heat of fusion and heat of vaporization of ice and water respectively by sketching temperature-time graph on heating ice.
- explain the process of evaporation and the difference between boiling and evaporation.
- explain that evaporation causes cooling.

Conceptual linkage

This unit is built on

Temperature Scales - Science-IV

Evaporization - Science-V

Thermal Expansion - Science-VIII

This unit leads to:

Thermodynamics - Physics-XI

Major Concepts

- **8.1 Temperature and heat**
- **8.2 Thermometer**
- **8.3 Specific heat capacity**
- **8.4 Latent heat of fusion**
- **8.5 Latent heat of vaporization**
- **8.6 Evaporation**
- **8.7 Thermal expansion**

- list the factors which influence surface evaporation.
- describe qualitatively the thermal expansion of solids (linear and volumetric expansion).
- explain thermal expansion of liquids (real and apparent expansion).
- solve numerical problems based on the mathematical relations learnt in this unit.

INVESTIGATION SKILLS

The students will be able to:

- demonstrate that evaporation causes cooling.

SCIENCE, TECHNOLOGY AND SOCIETY CONNECTION

The students will be able to:

- explain that the bimetallic strip used in thermostat is based on different rate of expansion of different metals on heating.
- describe one everyday effect due to relatively large specific heat of water.
- list and explain some of the everyday applications and consequences of thermal expansion.
- describe the use of cooling caused by evaporation in refrigeration process without using harmful CFC.

Figure 8.1: Heat is needed for cooking.

We use heat not only for cooking but also for doing other jobs. For example, changing heat to mechanical energy, electrical energy, etc. This can be done only if we have basic understanding about heat. Heat is an important concept in Physics. People have been trying to explain the nature of heat throughout the history of mankind. A quantitative study of thermal phenomena requires a careful definition of such important terms **as heat, temperature** and **internal energy.** In this unit, we shall discuss various concepts related to heat, temperature, measurements of temperature and various thermal phenomena.

8.1 TEMPERATURE AND HEAT

When we touch a body, we feel it hot or cold. The temperature of a body tells us how hot or cold a body is. Thus

Temperature of a body is the degree of hotness or coldness of the body.

A candle flame is hot and is said to be at high temperature. Ice on the other hand is cold and is said to be at low temperature. Our sense of touch is a simple way to know how much hot or cold a body is. However, this temperature sense is some what approximation and unreliable. Moreover, it is not always safe to touch a hot body. What we need is a reliable and practicable method to determine the relative hotness or coldness of bodies.

To understand the concept of temperature, it is useful to understand the terms, **thermal contact** and **thermal equilibrium**. To store ice in summer, people wrap it with cloth or keep it in wooden box or in thermos flask. In this way, they avoid the thermal contact of ice with its hot surroundings otherwise ice will soon melt away. Similarly, when you place a cup of hot tea or water in a room, it cools down gradually. Does it continue cooling? It stops cooling as it reaches the room temperature. Thus, temperature determines the direction of flow of heat. Heat flows from a hot body to a cold body until thermal equilibrium is reached.

What happens when we touch a hot body? Take two bodies having different temperatures. Bring them in contact with each other. The temperature of the hot body falls. It looses energy. This energy enters the cold body at lower temperature. Cold body gains energy and its temperature rises. The transfer of energy continues till both the bodies have the same temperature. The form of energy that is transferred from a hot body to a cold body is called heat. Thus

Heat is the energy that is transferred from one body to the other in thermal contact with each other as a result of the difference of temperature between them.

DO YOU KNOW

The crocus flower is a natural thermometer. It opens when the temperature is precisely 23°C and closes when the temperature drops.

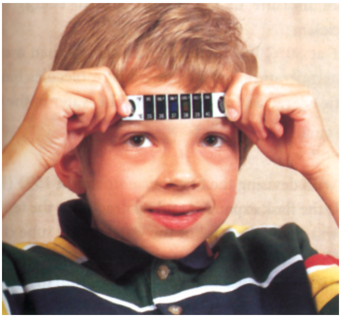


Figure 8.2: A strip thermometer

Heat is therefore, called as the **energy in transit.** Once heat enters a body, it becomes its **internal energy** and no longer exists as heat energy.

What is internal energy of a body?

The sum of kinetic energy and potential energy associated with the atoms, molecules and particles of a body is called its internal energy.

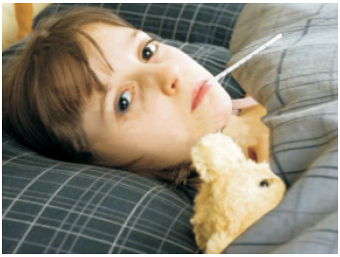


Figure 8.3: A thermometer shows body temperature.

Internal energy of a body depends on many factors such as the mass of the body, kinetic and potential energies of molecules etc. Kinetic energy of an atom or molecule is due to its motion which depends upon the temperature. Potential energy of atoms or molecules is the stored energy due to intermolecular forces.

8.2 THERMOMETER

A device that is used to measure the temperature of a body is called **thermometer.** Some substances have property that changes with temperature. Substances that show a change with temperature can be used as a thermometric material. For example, some substances expand on heating, some change their colours, some change their electric resistance, etc. Nearly all the substances expand on heating. Liquids also expand on heating and are suitable as thermometric materials. Common thermometers are generally made using some suitable liquid as thermometric material. A thermometric liquid should have the following properties:

- It should be visible.
- It should have uniform thermal expansion.
- It should have a low freezing point.
- It should have a high boiling point.
- It should not wet glass.
- It should be a good conductor of heat.
- It should have a small specific heat capacity.

Mini Exercise

1. Which of the following substances have greater average kinetic energy of its molecules at 10°C?
   (a) steel (b) copper
   (c) water (d) mercury
2. Every thermometer makes use of some property of a material that varies with temperature. Name the property used in:
   (a) strip thermometers
   (b) mercury thermometers

LIQUID-IN-GLASS THERMOMETER

A liquid-in-glass thermometer has a bulb with a long capillary tube of uniform and fine bore such as shown in figure 8.4. A suitable liquid is filled in the bulb. When the bulb contacts a hot object, the liquid in it expands and rises in the tube. The glass stem of a thermometer is thick and acts as a cylindrical lens. This makes it easy to see the liquid level in the glass tube.

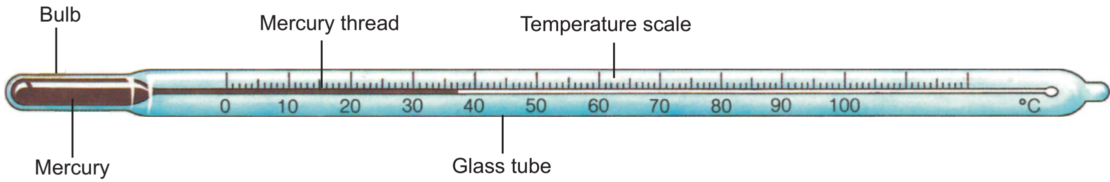


Figure 8 4: A mercury - in - glass thermometer

Mercury freezes at-39 °C and boils at 357 °C. It has all the thermometric properties listed above. Thus mercury is one of the most suitable thermometric material. Mercury-in-glass thermometers are widely used in laboratories, clinics and houses to measure temperatures in the range from -10 °C to 150 °C.

LOWER AND UPPER FIXED POINTS

A thermometer has a scale on its stem. This scale has two fixed points. The lower fixed point is marked to show the position of liquid in the thermometer when it is placed in ice. Similarly, upper fixed point is marked to show the position of liquid in the thermometer when it is placed in steam at standard pressure above boiling water.

SCALES OF TEMPERATURE

A scale is marked on the thermometer. The temperature of the body in contact with the thermometer can be read on that scale. Three scales of temperature are in common use. These are:

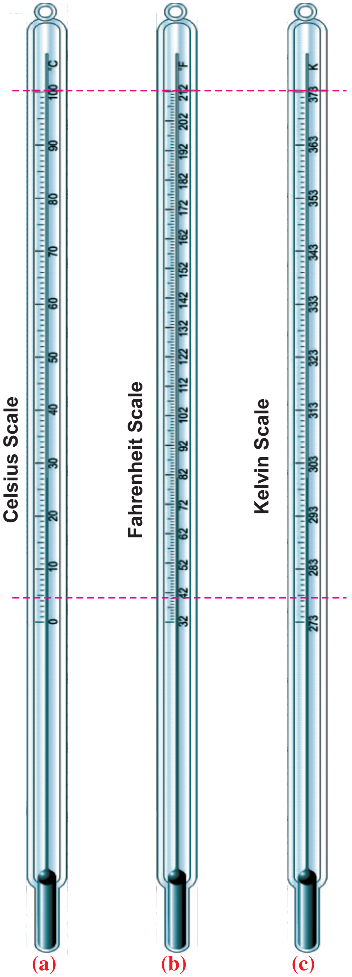


Figure 8.5: Various scales of temperature.

(i) Celsius scale or centigrade scale

(ii) Fahrenheit scale

(iii) Kelvin scale

On Celsius scale, the interval between lower and upper fixed points is divided into 100 equal parts as shown in figure 8.5(a). The lower fixed point is marked as 0 °C and the upper fixed point is marked as 100 °C.

On Fahrenheit scale, the interval between lower and upper fixed points is divided into 180 equal parts. Its lower fixed point is marked as 32 °F and upper fixed point is marked as 212 °F (Figure 8.5-b).

In SI units, the unit of temperature is kelvin (K) and its scale is called Kelvin scale of temperature as shown in figure 8.5 (c). The interval between the lower and upper fixed points is divided into 100 equal parts. Thus, a change in 1°C is equal to a change of 1K. The lower fixed point on this scale corresponds to 273 K and the upper fixed point is referred as 373 K. The zero on this scale is called the absolute zero and is equal to - 273 °C.

CONVERSION OF TEMPERATURE FROM ONE SCALE INTO OTHER TEMPERATURE SCALE

From Celsius to Kelvin Scale

The temperature T on Kelvin scale can be obtained by adding 273 in the temperature C on Celsius scale. Thus

$$T\,(\mathrm{K}) = 273 + C \qquad \ldots \quad \ldots \quad \ldots \quad (8.1)$$

EXAMPLE 8.1

What will be the temperature on Kelvin scale of temperature when it is 20 °C on Celsius scale?

SOLUTION

$C = 20\ °\mathrm{C}$

as $T = 273 + C$

$T = 273 + 20 = 293\ \mathrm{K}$

Do You Know?

Sun's core	15 000 000 °C
Sun's surface	6000 °C
Electric lamp	2500 °C
Gas lamp	1580 °C
Boiling water	100 °C
Human body	37 °C
Freezing water	0 °C
Ice in freezer	-18 °C
Liquid oxygen	-180 °C

FROM KELVIN TO CELSIUS SCALE

The temperature on Celsius scale can be found by subtracting 273 from the temperature in Kelvin Scale. Thus

$$C = T\,(\text{K}) - 273 \qquad \ldots \quad \ldots \quad (8.2)$$

EXAMPLE 8.2

Change 300K on Kelvin scale into Celsius scale of temperature.

SOLUTION

$$T = 300\ \text{K}$$

Since $C = T\,(\text{K}) - 273$

$\therefore$ $C = (300 - 273)\ ^\circ\text{C}$

or $C = 27\ ^\circ\text{C}$

FROM CELSIUS TO FAHRENHEIT SCALE

Since 100 divisions on Celsius scale are equal to 180 divisions on Fahrenheit scale. Therefore, each division on Celsius scale is equal to 1.8 divisions on Fahrenheit scale. Moreover, 0°C corresponds to 32°F.

$$\therefore \qquad F = 1.8C + 32 \qquad \ldots \quad \ldots \quad (8.3)$$

Here F is the temperature on Fahrenheit scale and C is the temperature on Celsius scale.

EXAMPLE 8.3

Convert 50°C on Celsius scale into Fahrenheit temperature scale.

SOLUTION

$C = 50\ ^\circ\text{C}$

Since $F = (1.8 \times C + 32)$

$F = (1.8 \times 50 + 32)$

or $F = 122\ ^\circ\text{F}$

Thus, 50 °C on Celsius scale is 122 °F on Fahrenheit scale.

DO YOU KNOW?

A clinical thermometer is used to measure the temperature of human body. It has a narrow range from 35 °C to 42 °C. It has a constriction that prevents the mercury to return. Thus, its reading does not change until reset.

FROM FAHRENHEIT TO CELSIUS SCALE

From equation 8.3, we can find the temperature on Celsius scale from Fahrenheit Scale.

EXAMPLE 8.4

Convert 100 °F into the temperature on Celsius scale.

SOLUTION

$$F = 100\ °F$$

Since $1.8\,C = F - 32$

$$\therefore \quad = 100 - 32$$

or $1.8\,C = 68$

or $C = 68/1.8$

or $C = 37.8\ °C$

Thus, 100°F is equal to 37.8°C.

Table 8.1: Specific heat of some common substances

Substance	Specific heat $Jkg^{-1}K^{-1}$
Alcohol	2500.0
Aluminium	903.0
Bricks	900.0
Carbon	121.0
Clay	920.0
Copper	387.0
Ether	2010.0
Glass	840.0
Gold	128.0
Granite	790.0
Ice	2100.0
Iron	470.0
Lead	128.0
Mercury	138.6
Sand	835.0
Silver	235.0
Soil (dry)	810.0
Steam	2016.0
Tungsten	134.8
Turpentine	1760.3
Water	4200.0
Zinc	385.0

8.3 SPECIFIC HEAT CAPACITY

Generally, when a body is heated, its temperature increases. Increase in the temperature of a body is found to be proportional to the amount of heat absorbed by it. It has also been observed that the quantity of heat ΔQ required to raise the temperature ΔT of a body is proportional to the mass m of the body. Thus

$$\Delta Q \propto m\,\Delta T$$

or $$\Delta Q = c\,m\,\Delta T \quad \ldots \ldots \ldots \ldots \quad (8.4)$$

Here ΔQ is the amount of heat absorbed by the body and c is the constant of proportionality called the specific heat capacity or simply specific heat.

The specific heat of a substance is defined as

Specific heat of a substance is the amount of heat required to raise the temperature of 1 kg mass of that substance through 1K.

Mathematically,

$$c = \frac{\Delta Q}{m\,\Delta T} \quad \ldots \ldots \ldots \ldots \ldots \ldots \quad (8.5)$$

In SI units, mass m is measured in kilogramme (kg), heat ΔQ is measured in joule (J) and temperature increase ΔT is taken in kelvin (K). Hence, SI unit of

specific heat is $Jkg^{-1}K^{-1}$. Specific heats of some common substances are given in Table 8.1.

IMPORTANCE OF LARGE SPECIFIC HEAT CAPACITY OF WATER

Specific heat of water is 4200 $Jkg^{-1}K^{-1}$ and that of dry soil is about 810 $Jkg^{-1}K^{-1}$. As a result the temperature of soil would increase five times more than the same mass of water by the same amount of heat. Thus, the temperature of land rises and falls more rapidly than that of the sea. Hence, the temperature variations from summer to winter are much smaller at places near the sea than land far away from the sea.

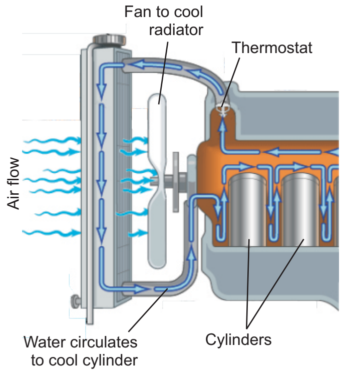


Figure 8.6: A Cooling system in automobile.

Water has a large specific heat capacity. For this reason, it is very useful in storing and carrying thermal energy due to its high specific heat capacity. The cooling system of automobiles uses water to carry away unwanted thermal energy. In an automobile, large amount of heat is produced by its engine due to which its temperature goes on increasing. The engine would cease unless it is not cooled down. Water circulating around the engine as shown by arrows in figure 8.6 maintains its temperature. Water absorbs unwanted thermal energy of the engine and dissipates heat through its radiator.

In central heating systems such as shown in figure 8.7, hot water is used to carry thermal energy through pipes from boiler to radiators. These radiators are fixed inside the house at suitable places.

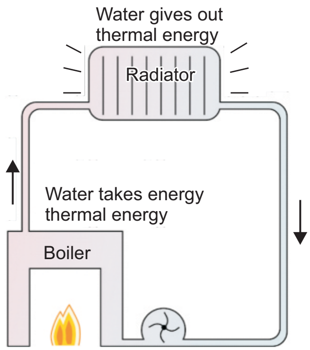


Figure 8.7: Central heating system

EXAMPLE 8.5

A container has 2.5 litres of water at 20°C. How much heat is required to boil the water?

SOLUTION

Volume of water $= 2.5$ litres

Mass of water $m = 2.5$ kg

(since density of water is 1000 kgm^{-3} or 1kgL^{-1})

Specific heat of water $c = 4200 \text{ Jkg}^{-1} \text{ K}^{-1}$

Initial temperature $t_1 = 20^{\circ}\text{C}$

Final temperature $t_2 = 100^{\circ}\text{C}$

Temperature Increase $\Delta T = t_2 - t_1$

$= 100^{\circ}\text{C} - 20^{\circ}\text{C}$

$= 80\ ^{\circ}\text{C} \text{ or } 80 \text{ K}$

Since $Q = c\, m \Delta T$

$\therefore$ $Q = 4200 \text{ Jkg}^{-1}\text{K}^{-1} \times 2.5 \text{ kg} \times 80 \text{ K}$

or $Q = 840\ 000 \text{ J}$

Thus, required amount of heat is 840 000 J or 840 kJ.

HEAT CAPACITY

How much heat a body can absorb depends on many factors. Here we define a quantity called heat capacity of a body as:

Heat capacity of a body is the quantity of thermal energy absorbed by it for one kelvin (1 K) increase in its temperature.

Thus, if the temperature of a body increases through ΔT on adding ΔQ amount of heat, then its heat capacity will be $\dfrac{\Delta Q}{\Delta T}$

Putting the value of ΔQ, we get

$$\text{Heat capacity} = \frac{\Delta Q}{\Delta T} = \frac{m\, c\, \Delta T}{\Delta T}$$

$$\therefore \text{ Heat capacity} = mc \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (8.6)$$

Equation (8.6) shows that heat capacity of a body is equal to the product of its mass of the body and its specific heat capacity. For example, heat capacity of 5 kg of water is (5 kg **x** 4200 Jkg^{-1} K^{-1}) 21000 JK^{-1}. That is; 5 kg of water needs 21000 joules of heat for every 1 K rise in its temperature. Thus, larger is the quantity of a substance, larger will be its heat capacity.

DO YOU KNOW?

The presence of large water reservoirs such as lakes and seas keep the climates of nearby land moderate due to the large heat capacity of these reservoirs.

8.4 CHANGE OF STATE

Matter can be changed from one state to another. For such a change to occur, thermal energy is added to or removed from a substance.

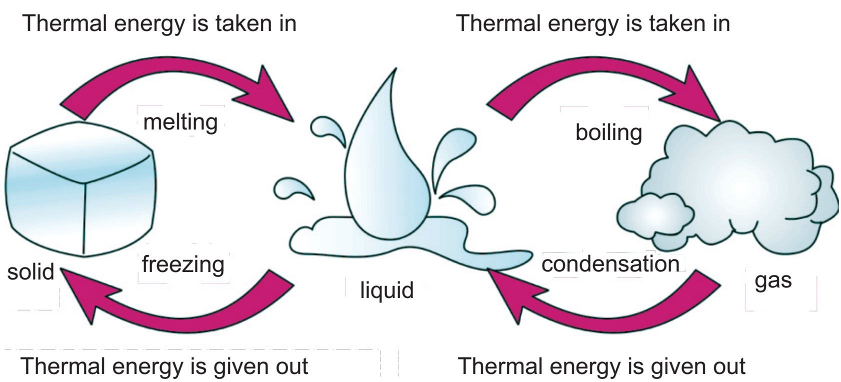


Figure 8.8: Heat energy brings about change of state in matter

ACTIVITY 8.1

Take a beaker and place it over a stand. Put small pieces of ice in the beaker and suspend a thermometer in the beaker to measure the temperature of ice.

Now place a burner under the beaker. The ice will start melting. The temperature of the mixture containing ice and water will not increase above 0°C until all the ice melts and we get water at 0°C. If this water at 0°C is further heated, its temperature will begin to increase above 0 °C as shown by the graph in figure. 8.9.

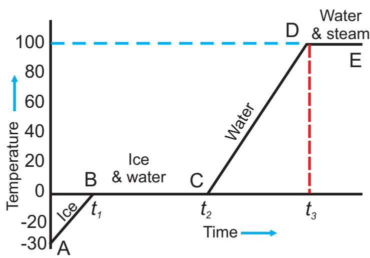


Figure 8.9: A graph of temperature and time showing change of state of ice into water and steam.

Part AB: On this portion of the curve, the temperature of ice increases from -30 °C to 0 °C.

Part BC: When the temperature of ice reaches 0 °C, the ice water mixture remains at this temperature until all the ice melts.

Part CD: The temperature of the substance gradually increases from 0 °C to 100 °C. The amount of energy so added is used up in increasing the temperature of water.

Part DE: At 100 °C water begins to boil and changes into steam. The temperature remains 100 °C till all the water changes into steam.

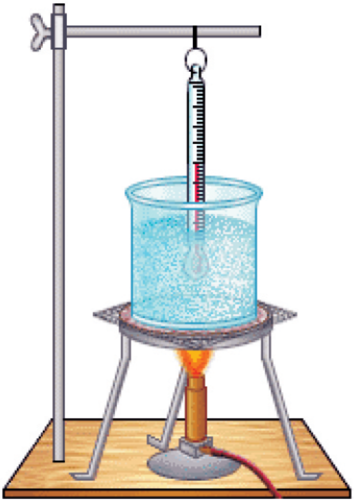


Figure 8.10: Heating ice

8.5 LATENT HEAT OF FUSION

When a substance is changed from solid to liquid state by adding heat, the process is called melting or fusion. The temperature at which a solid starts melting is called its **fusion point** or **melting point.** When the process is reversed i.e. when a liquid is cooled, it changes into solid state. The temperature at which a substance changes from liquid to solid state is called its **freezing point.** Different substances have different melting points. However, the freezing point of a substance is the same as its melting point.

Heat energy required to change unit mass of a substance from solid to liquid state at its melting point without change in its temperature is called its latent heat of fusion.

It is denoted by H_f

$$H_f = \frac{\Delta Q_f}{m}$$

or $$\Delta Q_f = m H_f \quad \dots \dots \dots \dots \dots (8.7)$$

Ice changes at 0 °C into water. Latent heat of fusion of ice is 3.36 x10^5 Jkg^{-1}. That is; 3.36x10^5 joule heat is required to melt 1 kg of ice into water at 0 °C.

EXPERIMENT 8.1

Take a beaker and place it over a stand. Put small pieces of ice in the beaker and suspend a thermometer in the beaker to measure the temperature. Place a burner under the beaker. The ice will start melting. The temperature of the mixture containing ice and water will not increase above 0°C until all the ice melts. Note the time which the ice takes to melt completely into water at 0°C.

Continue heating the water at 0°C in the beaker. Its temperature will begin to increase. Note the time which the water in the beaker takes to reach its boiling point at 100°C from 0°C.

Draw a temperature-time graph such as shown in figure 8.11. Calculate the latent heat of fusion of ice from the data as follows:

Let mass of ice = m

Finding the time from the graph:

Time taken by ice to melt completely at 0°C $= t_f \quad = t_2 - t_1 \quad = 3.6$ min.

Time taken by water to heat from 0°C to 100°C $= t_o \quad = t_3 - t_2 \quad = 4.6$ min.

Specific heat of water c $= 4200\ \mathrm{Jkg^{-1}K^{-1}}$

Increase in the temperature of water $= \Delta T = 100\ ^{o}\mathrm{C} \quad = 100\ \mathrm{K}$

Heat required by water from 0°C to 100°C

$$= \Delta Q = m\,c\,\Delta T$$
$$= m \times 4200\ \mathrm{Jkg^{-1}K^{-1}} \times 100\ \mathrm{K}$$
$$= m \times 420\,000\ \mathrm{Jkg^{-1}}$$
$$= m \times 4.2 \times 10^5\ \mathrm{Jkg^{-1}}$$

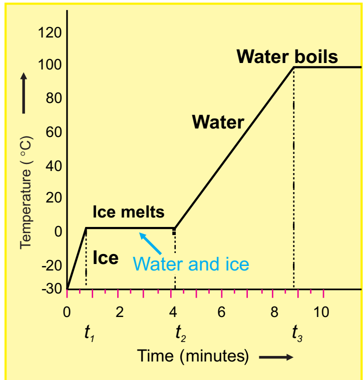


Figure 8.11: Temperature-time graph as ice changes into water that boils as heating continues.

Heat A Q is supplied to water in time t_o to raise its temperature from 0°C to 100°C. Hence, the rate of absorbing heat by water in the beaker is given by

$$\text{Rate of absorbing heat} = \frac{\Delta Q}{t_o}$$

$$\therefore \text{ Heat absorbed in time } t_f = \Delta Q_f = \frac{\Delta Q \times t_f}{t_o}$$

$$= \Delta Q \times \frac{t_f}{t_o}$$

Since $\Delta Q_f = m \times H_f$ (from *eq. 8.7)*

Putting the values, we get

$$m \times H_f = m \times 4.2 \times 10^5\ \mathrm{Jkg^{-1}} \times \frac{t_f}{t_o}$$

or

$$H_f = 4.2 \times 10^5\ \mathrm{Jkg^{-1}} \times \frac{t_f}{t_o}$$

The values of t_f and t_o can be found from the graph. Put the values in the above equation to get

$$H_f = 4.2 \times 10^5\ \mathrm{Jkg^{-1}} \times \frac{3.6\ \text{min.}}{4.6\ \text{min.}}$$

$$= 3.29 \times 10^5\ \mathrm{Jkg^{-1}}$$

The latent heat of fusion of ice found by the above experiment is $3.29 \times 10^5\ \mathrm{Jkg^{-1}}$ while its actual value is $3.36 \times 10^5\ \mathrm{Jkg^{-1}}$.

8.6 LATENT HEAT OF VAPORIZATION

When heat is given to a liquid at its boiling point, its temperature remains constant. The heat energy given to a liquid at its boiling point is used up in changing its state from liquid to gas without any increase in its temperature. Thus

The quantity of heat that changes unit mass of a liquid completely into gas at its boiling point without any change in its temperature is called its latent heat of vaporization.

It is denoted by H_v

$$H_v = \frac{\Delta Q_v}{m}$$

or $$\Delta Q_v = m H_v \quad \ldots \ldots \ldots \ldots \ldots (8.8)$$

When water is heated, it boils at 100°C under standard pressure. Its temperature remains 100°C until it is changed completely into steam. Its latent heat of vaporization is 2.26 x10^6 J kg^{-1}. That is; one kilogramme of water requires 2.26x10^6 joule heat to change it completely into gas (steam) at its boiling point. The value of melting point, boiling point, latent heat of fusion and vaporization of some of the substances is given in Table 8.2.

Table 8.2: Melting point, boiling point, latent heat of fusion and latent heat of vaporization of some common substances.

Substance	Melting point (°C)	Boiling point (°C)	Heat of fusion ($kJkg^{-1}$)	Heat of vaporization ($kJkg^{-1}$)
Aluminium	660	2450	39.7	10500
Copper	1083	2595	205.0	4810
Gold	1063	2660	64.0	1580
Helium	-270	-269	5.2	21
Lead	327	1750	23.0	858
Mercury	-39	357	11.7	270
Nitrogen	-210	-196	25.5	200
Oxygen	-219	-183	13.8	210
Water	0	100	336.0	2260

EXPERIMENT 8.2

At the end of experiment 8.1, the beaker contains boiling water. Continue heating water till all the water changes into steam. Note the time which the

water in the beaker takes to change completely into steam at its boiling point 100°C.

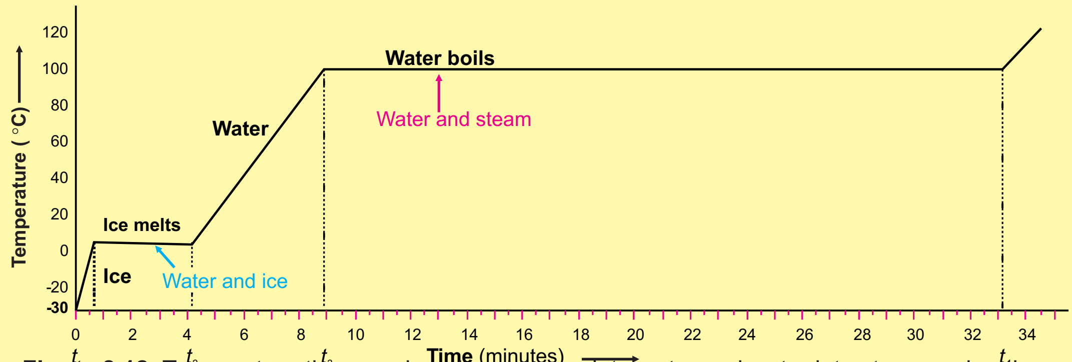


Figure 8.12: Temperature-time graph as ice changes into water and water into steam on heating.

Extend the temperature-time graph such as shown in figure 8.12. Calculate the latent heat of fusion of ice from the data as follows:

Let Mass of ice $= m$

Time t0 taken to heat water from 0°C to 100°C (melt) $= t_o = t_3 - t_2 = 4.6$ min.

Time taken by water at 100°C to change it into steam $= t_v = t_4 - t_3 = 24.4$ min.

Specific heat of water c $= 4200\ \text{Jkg}^{-1}\text{K}^{-1}$

Increase in the temperature of water $= \Delta T = 100^{\circ}\text{C} = 100\ \text{K}$

Heat required to heat water from 0°C to 100°C $= \Delta Q = m\,c\,\Delta T$

$$= m \times 4200\ \text{Jkg}^{-1}\text{K}^{-1} \times 100\ \text{K}$$
$$= m \times 420\ 000\ \text{Jkg}^{-1}$$
$$= m \times 4.2 \times 10^{5}\ \text{Jkg}^{-1}$$

As burner supplies heat ΔQ to water in time t_o to raise its temperature from 0°C to 100°C. Hence, the rate at which heat is absorbed by the beaker is given by

Rate of absorbing heat $= \dfrac{\Delta Q}{t_o}$

$\therefore$ Heat absorbed in time t_v $= \Delta Q_v = \dfrac{\Delta Q \times t_v}{t_o}$

$$= \Delta Q \times \frac{t_v}{t_o}$$

Since $\Delta Q_v = m \times H_v$ (from eq.8.8)

Putting the values, we get

$$m \times H_v = m \times 4.2\times10^5 \text{ Jkg}^{-1} \times \frac{t_v}{t_o}$$

or $$H_v = 4.2\times10^5 \text{ Jkg}^{-1} \times \frac{t_v}{t_o}$$

Putting the values of t_v and t_o from the graph, we get

$$H_v = 4.2\times10^5 \text{ Jkg}^{-1} \times \frac{24.4 \text{ min.}}{4.6 \text{ min.}}$$

$$= 2.23 \times10^6 \text{ Jkg}^{-1}$$

The latent heat of vaporization of water found by the above experiment is $2.23\text{x}10^6$ Jkg^{-1} while its actual value is $2.26\text{x}10^6$ Jkg^{-1}.

8.7 THE EVAPORATION

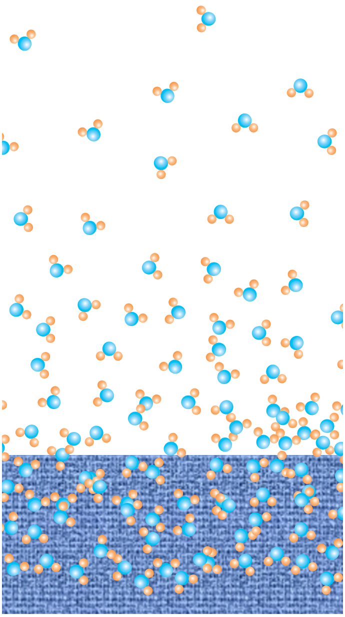


Figure 8.13: Evaporation is escaping out of fast moving water molecules from the surface of a liquid without heating.

Take some water in a dish. The water in the dish will disappear after sometime. It is because the molecules of water are in constant motion and possess kinetic energy. Fast moving molecules escape out from the surface of water and goes into the atmosphere. This is called **evaporation.** Thus

Evaporation is the changing of a liquid into vapours (gaseous state) from the surface of the liquid without heating it.

Unlike boiling, evaporation takes place at all temperatures but only from the surface of a liquid. The process of boiling takes place at a certain fixed temperature which is the boiling point of that liquid. At boiling point, a liquid is changing into vapours not only from the surface but also within the liquid. These vapours come out of the boiling liquid as bubbles which breakdown on reaching the surface.

Evaporation plays an important role in our daily life. Wet clothes dry up rapidly when spread. Evaporation causes cooling. Why? During evaporation fast moving molecules escape out from the surface of the liquid. Molecules that have lower kinetic energies are left behind. This lowers the average kinetic energy of the liquid molecules and the temperature of the

Mini Exercise

1. How specific heat differs from heat capacity?
2. Give two uses of cooling effect by evaporation.
3. How evaporation differs from vaporization?

liquid. Since temperature of a substance depends on the average kinetic energy of its molecules. Evaporation of perspiration helps to cool our bodies.

Evaporation takes place at all temperature from the surface of a liquid. The rate of evaporation is affected by various factors.

TEMPERATURE

Why wet clothes dry up more quickly in summer than in winter? At higher temperature, more molecules of a liquid are moving with high velocities. Thus, more molecules escape from its surface. Thus, evaporation is faster at high temperature than at low temperature.

SURFACE AREA

Why water evaporates faster when spread over large area? Larger is the surface area of a liquid, greater number of molecules has the chance to escape from its surface.

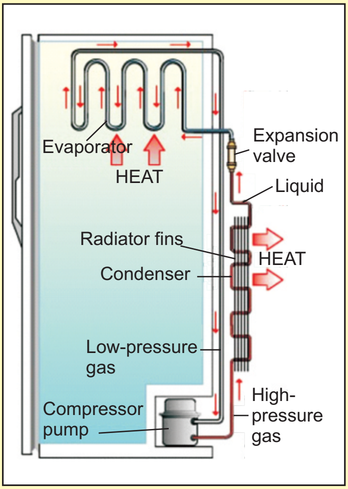
WIND

Wind blowing over the surface of a liquid sweeps away the liquid molecules that have just escaped out. This increases the chance for more liquid molecules to escape out.

NATURE OF THE LIQUID

Does spirit and water evaporate at the same rate? Liquids differ in the rate at which they evaporate. Spread a few drops of ether or spirit on your palm. You feel cold, why?

COOLING IN REFRIGERATORS

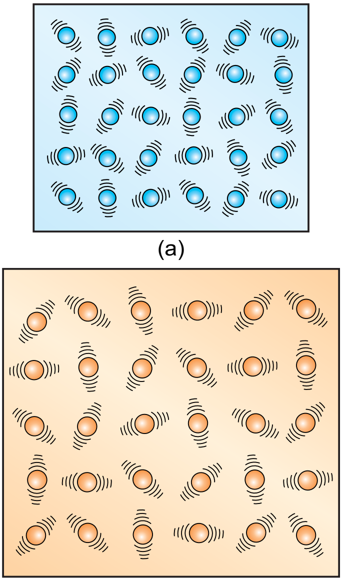


Cooling is produced in refrigerators by evaporation of a liquified gas. This produces cooling effect. Freon, a CFC, was used as a refrigerant gas. But its use has been forbidden when it was known that CFC is the cause of ozone depletion in the upper atmosphere which results increase in amount of UV rays from the Sun. The rays are harmful to all living matter. Freon gas is now replaced by Ammonia and other substances which are not harmful to the environment.

8.8 THERMAL EXPANSION

Most of the substances solids, liquids and gases expand on heating and contract on cooling. Their thermal expansions and contractions are usually small and are not noticeable. However, these expansions and contractions are important in our daily life.

The kinetic energy of the molecules of an object depends on its temperature. The molecules of a solid vibrate with larger amplitude at high temperature than



(a)

(b)

Figure 8.14: Molecules of an object moving with **(a)** smaller amplitude at low temperature **(b)** larger amplitude at high temperature.

at low temperature. Thus, on heating, the amplitude of vibration of the atoms or molecules of an object increases. They push one another farther away as the amplitude of vibration increases. Thermal expansion results an increase in length, breadth and thickness of a substance.

LINEAR THERMAL EXPANSION IN SOLIDS

It has been observed that solids expand on heating and their expansion is nearly uniform over a wide range of temperature. Consider a metal rod of length L_0 at certain temperature T_o. Let its length on heating to a temperature T becomes L Thus

Increase in length of the rod $= \Delta L = L - L_o$

Increase in temperature $= \Delta T = T - T_o$

It is found that change in length AL of a solid is directly proportional to its original length L_0, and the change in temperature ΔT. That is;

$$\Delta L \propto L_o \Delta T$$

or $$\Delta L = \alpha L_o \Delta T \quad \ldots \quad \ldots \quad \ldots \quad (8.9)$$

or $$L - L_o = \alpha L_o \Delta T$$

or $$L = L_o (1 + \alpha \Delta T) \quad \ldots \quad \ldots \quad (8.10)$$

where α is called the **coefficient of linear thermal expansion of the substance.**

From equation (8.9), we get

$$\alpha = \frac{\Delta L}{L_o \Delta T} \quad \ldots \quad \ldots \quad \ldots \quad (8.11)$$

Thus, we can define the coefficient of linear expansion α of a substance as the fractional increase in its length per kelvin rise in temperature. Table 8.3 gives coefficient of linear thermal expansion of some common solids.

Table 8.3: Coefficient of linear thermal expansion (α) of some common solids.

Substance	α (K^{-1})
Aluminium	2.4×10^{-5}
Brass	1.9×10^{-5}
Copper	1.7×10^{-5}
Steel	1.2×10^{-5}
Silver	1.93×10^{-5}
Gold	1.3×10^{-5}
Platinum	8.6×10^{-5}
Tungsten	0.4×10^{-5}
Glass (pyrex)	0.4×10^{-5}
Glass(ordinary)	0.9×10^{-5}
Concrete	1.2×10^{-5}

EXAMPLE 8.6

A brass rod is 1 m long at 0°C. Find its length at 30°C. (Coefficient of linear expansion of brass $=1.9\text{x}10^{-5}K^{-1}$)

SOLUTION

$L_o = 1\text{m}$

$t = 30^{o}\text{C}$

$t_o = 0^{o}\text{C}$

$T_o = 0+273 = 273\text{K}$

$T = 30 + 273 = 303\text{K}$

$\Delta T = T - T_o$

$= 303\text{ K} - 273\text{ K}$

$= 30\text{ K}$

$\alpha = 1.9 \times 10^{-5}\text{K}^{-1}$

since $L = L_o(1 + \alpha \ \Delta T)$

$L = 1\text{m} \times (1 + 1.9 \times 10^{-5}\text{K}^{-1} \times 30\text{K})$

$L = 1.00057\text{ m}$

Hence, the length of the brass bar at 30°C will be 1.00057 m.

VOLUME THERMAL EXPANSION

The volume of a solid also changes with the change in temperature and is called volume thermal expansion or cubical thermal expansion. Consider a solid of initial volume V_o at certain temperature T_o. On heating the solid to a temperature T, let its volume becomes V, then

Change in the volume of a solid $\Delta V = V - V_o$

and Change in temperature $\Delta T = T - T_o$

Like linear expansion, the change in volume ΔV is found to be proportional to its original volume V_o and change in temperature ΔT. Thus

$$\Delta V \propto V_o \Delta T$$

or
$$\Delta V = \beta V_o \Delta T \quad \dots \dots \dots \dots \quad (8.12)$$

$$V - V_o = \beta V_o \Delta T$$

$$\therefore \quad V = V_o(1 + \beta \Delta T) \quad \dots \dots \dots \dots \quad (8.13)$$

where β is the temperature coefficient of volume expansion. Using equation 8.12, we get

Table 8.4: Coefficient of volume expansion of various substances.

Substance	$\beta\ (\text{K}^{-1})$
Aluminium	7.2×10^{-5}
Brass	6.0×10^{-5}
Copper	5.1×10^{-5}
Steel	3.6×10^{-5}
Platinum	27.0×10^{-5}
Glass(ordinary)	2.7×10^{-5}
Glass(pyrex)	1.2×10^{-5}
Glycerine	53×10^{-5}
Mercury	18×10^{-5}
Water	21×10^{-5}
Air	3.67×10^{-3}
Carbon dioxide	3.72×10^{-3}
Hydrogen	3.66×10^{-3}

$$\beta = \frac{\Delta V}{V_o \Delta T} \qquad \dots \quad \dots \quad \dots \quad \dots \quad \dots (8.14)$$

Thus, we can define the temperature coefficient of volume expansion β as the fractional change in its volume per kelvin change in temperature. The coefficients of linear expansion and volume expansion are related by the equation:

$$\beta = 3\,\alpha \qquad \dots \quad \dots \quad \dots \quad \dots \quad \dots (8.15)$$

Values of β for different substances are given in Table 8.4.

EXAMPLE 8.7

Find the volume of a brass cube at 100°C whose side is 10 cm at 0°C. (coefficient of linear thermal expansion of brass = 1.9x 10^{-5} $K^{-}1$).

SOLUTION

L_o = 10cm = 0.1 m

T_o = 0^o C = (0 + 273) K = 273 K

T = 100^o C = (100 + 273) K = 373 K

$\Delta T = T - T_o$

= 373 K – 273 K = 100 K

$\alpha = 1.9 \times 10^{-5}\ K^{-1}$

as $\beta = 3\,\alpha$

Therefore $\beta = 3 \times 1.9 \times 10^{-5}\ K^{-1}$

$= 5.7 \times 10^{-5}\ K^{-1}$

initial volume $V_o = L_o^3 = (0.1\ m)^3$

$= 0.001\ m^3 = 10^{-3}\ m^3$

Since $V = V_o\,(1 + \beta \Delta T)$

Hence $V = 10^{-3}\ m^3 \times (1 + 5.7 \times 10^{-5}\ K^{-1} \times 100\ K)$

or $V = 10^{-3}\ m^3 \times (1 + 5.7 \times 10^{-3})$

$= 10^{-3}\ m^3 \times (1 + 0.0057)$

$= 1.0057 \times 10^{-3}\ m^3$

Hence, the volume of brass cube at 100 °C will be $1.0057 \times 10^{-3} m^3$.

CONSEQUENCES OF THERMAL EXPANSION

Why gaps are left in railway tracks? The expansion of solids may damage the bridges, railway tracks and roads as they are constantly subjected to temperature changes. So provision is made during construction for expansion and contraction with temperature. For example, railway tracks buckled on a hot summer day due to expansion if gaps are not left between sections.

Figure 8.15: Gaps are left in railway tracks to compensate thermal expansion during hot season.

Bridges made of steel girders also expand during the day and contract during night. They will bend if their ends are fixed. To allow thermal expansion, one end is fixed while the other end of the girder rests on rollers in the gap left for expansion. Overhead transmission lines are also given a certain amount of sag so that they can contract in winter without snapping.

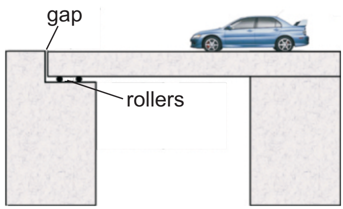


Figure 8.16: Bridges with rollers below one of their ends allow movements due to expansion and contraction.

APPLICATIONS OF THERMAL EXPANSION

Thermal expansion is used in our daily life. In thermometers, thermal expansion is used in temperature measurements. To open the cap of a bottle that is tight enough, immerse it in hot water for a minute or so. Metal cap expands and becomes loose. It would now be easy to turn it to open.

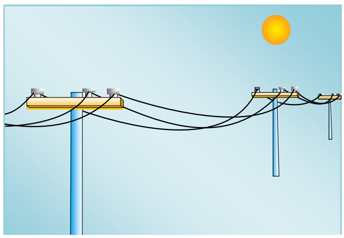


Figure 8.17: Wires on electric poles are given some sag to prevent breakina in winter.

To join steel plates tightly together, red hot rivets are forced through holes in the plates as shown in figure 8.18 (a). The end of hot rivet is then hammered. On cooling, the rivets contract and bring the plates tightly gripped.

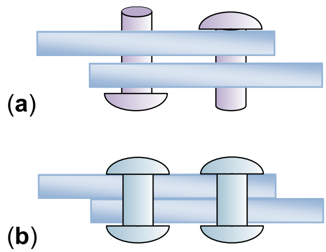


Figure 8.18 (a) Hot rivets inserted **(b)** after hammering, rivets are cold down.

Iron rims are fixed on wooden wheels of carts. Iron rims are heated. Thermal expansion allows them to slip over the wooden wheel. Water is poured on it to cool. The rim contracts and becomes tight over the wheel.

BIMETAL STRIP

A bimetal strip consists of two thin strips of different metals such as brass and iron joined together as shown in figure 8.19(a). On heating the strip, brass

expands more than iron. This unequal expansion causes bending of the strip as shown in figure 8. 19(b).

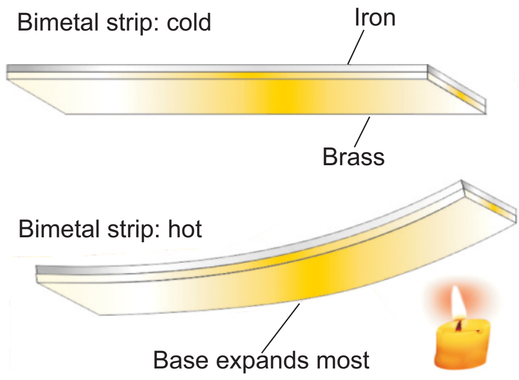


Figure 8.19 (a) A bimetal strip of brass and iron (b) Bending of brass-iron bimetal strip on heating due to the difference in their thermal expansion.

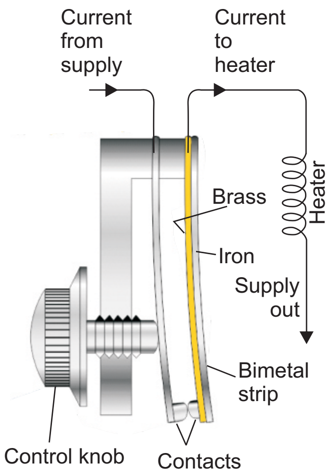


Figure 8.20: Bimetal thermostat breaks the electrical circuit at preset temperature.

Bimetal strips are used for various purposes. Bimetal thermometers are used to measure temperatures especially in furnaces and ovens. Bimetal strips are also used in thermostats. Bimetal thermostat switch such as shown in figure 8.20 is used to control the temperature of heater coil in an electric iron.

THERMAL EXPANSION OF LIQUIDS

The molecules of liquids are free to move in all directions within the liquid. On heating a liquid, the average amplitude of vibration of its molecules increases. The molecules push each other and need more space to occupy. This accounts for the expansion of the liquid when heated. The thermal expansion in liquids is greater than solids due to the weak forces between their molecules. Therefore, the coefficient of volume expansion of liquids is greater than solids.

Liquids have no definite shape of their own. A liquid always attains shape of the container in which it is poured. Therefore, when a liquid is heated, both liquid and the container undergo a change in their volume. Thus, there are two types of thermal volume expansion for liquid.

- Apparent volume expansion
- Real volume expansion

DO YOU KNOW?

Water on cooling below 4°C begins to expand until it reaches 0°C. On further cooling its volume increases suddenly as it changes into ice at 0°C. When ice is cooled below 0°C, it contracts i.e. its volume decreases like solids. This unusual expansion of water is called the **anomalous expansion of water.**

ACTIVITY

Take a long-necked flask. Fill it with some coloured liquid upto the mark A on its neck as shown in figure 8.21. Now start heating the flask from bottom. The liquid level first falls to B and then rises to C.

The heat first reaches the flask which expands and its volume increases. As a result liquid descends in the flask and its level falls to B. After sometime, the liquid begins to rise above B on getting hot. At certain temperature it reaches at C. The rise in level from A to C is due to the apparent expansion in the volume of the liquid. Actual expansion of the liquid is greater than that due to the expansion because of the expansion of the glass flask. Thus real expansion of the liquid is equal to the volume difference between A and C in addition to the volume expansion of the flask. Hence

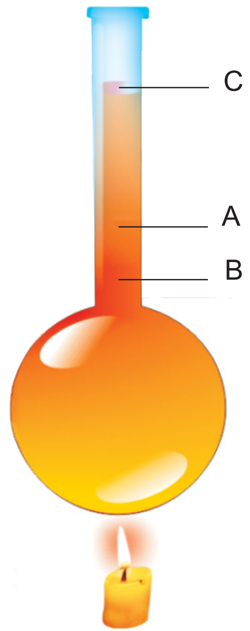


Figure 8.21: Real and apparent expansion of liquid.

Real expansion of the liquid = Apparent expansion of the liquid + Expansion of the flask

or BC = AC + AB ... ... (8.16)

The expansion of the volume of a liquid taking into consideration the expansion of the container also, is called the real volume expansion of the liquid. The real rate of volume expansion β_r of a liquid is defined as the actual change in the unit volume of a liquid for 1K (or 1°C) rise in its temperature. The real rate of volume expansion β_r is always greater than the apparent rate of volume expansion β_a by an amount equal to the rate of volume expansion of the container β_g. Thus

$$\beta_r = \beta_a + \beta_g \quad \dots \dots \dots (8.17)$$

It should be noted that different liquids have different coefficients of volume expansion.

SUMMARY

- The temperature of a body is the degree of hotness or coldness of the body.
- Thermometers are made to measure the temperature of a body or places.
- The lower fixed point is the mark that gives the position of mercury in the thermometer when it is placed in ice.
- The upper fixed point is the mark that shows the position of mercury in the thermometer when it is placed in steam from boiling water at standard pressure.
- Inter-conversion between scales:
  - From Celsius To Kelvin Scale: T(K)=273 + C
  - From Kelvin to Celsius Scale:

    $$C = T\,(K) - 273$$

  - From Celsius to Fahrenheit Scale:

    $$F = 1.8\,C + 32$$

- Heat is a form of energy and this energy is called heat as long as it is in the process of transfer from one body to another body. When a body is heated, the kinetic energy of its molecules increases, the average distances between the molecules increase.
- The specific heat of a substance is defined as the amount of heat required to raise the temperature of a unit mass of that substance through one degree centigrade (1°C) or one kelvin (1K).
- The heat required by unit mass of a substance at its melting point to change it from solid state to liquid state is called the latent heat of fusion.
- The quantity of heat required by the unit mass of a liquid at a certain constant temperature to change its state completely from liquid into gas is called the latent heat of vaporization.
- It has been observed that solids expand on heating and their expansion is nearly uniform over a wide range of temperature. Mathematically,

  $$L = L_o\,(1 + \alpha\,\Delta T)$$

- The thermal coefficient of linear expansion α of a substance is defined as the fractional increase in its length per kelvin rise in temperature.
- The volume of a solid changes with the change in temperature and is called as volume or cubical expansion.

  $$V = V_o\,(1 + \beta\Delta T)$$

- The thermal coefficient of volume expansion β is defined as the fractional change in its volume per kelvin change in temperature.
- There are two types of thermal volume expansion for liquids as well as for gases. Apparent volume expansion and real volume expansion.

QUESTIONS

8.1 Encircle the correct answer from the given choices.

i. Water freezes at

(a) 0°F (b) 32 °F

(c) -273 K (d) 0 K

ii. Normal human body temperature is

(a) 15°C (b)37°C

(c) 37 °F (d)98.6°C

iii. Mercury is used as thermometric material because it has

(a) uniform thermal expansion

(b) low freezing point

(c) small heat capacity

(d) all the above properties

iv. Which of the following material has large specific heat?

(a) copper (b) ice

(c) water (d) mercury

v. Which of the following material has large value of temperature coefficient of linear expansion?

(a) aluminum (b) gold

(c) brass (d) steel

vi. What will be the value of p for a solid for which a has a value of $2x10^{-5}K^{-1}$?

(a) $2x10^{-5}$ K^{-1}

(b) $6x10^{-5}$ K^{-1}

(c) $8x10^{-15}$ K^{-1}

(d) $8x10^{-5}$ K^{-1}

vii. A large water reservoir keeps the temperature of nearby land moderate due to

(a) low temperature of water

(b) low specific heat of water

(c) less absorption of heat

(d) large specific heat of water

viii. Which of the following affects evaporation?

(a) temperature

(b) surface area of the liquid

(c) wind

(d) all of the above

8.2 Why does heat flow from hot body to cold body?

8.3 Define the terms heat and temperature.

8.4 What is meant by internal energy of a body?

8.5 How does heating affect the motion of molecules of a gas?

8.6 What is a thermometer? Why mercury is preferred as a thermometric substance?

8.7 Explain the volumetric thermal expansion.

8.8 Define specific heat. How would you find the specific heat of a solid?

8.9 Define and explain latent heat of fusion.

8.10 Define latent heat of vaporization.

8.11 What is meant by evaporation? On what factors the evaporation of a liquid depends? Explain how cooling is produced by evaporation.

PROBLEMS

8.1 Temperature of water in a beaker is 50°C. What is its value in Fahrenheit scale?
(122 °F)

8.2 Normal human body temperature is 98.6°F. Convert it into Celsius scale and Kelvin scale.
(37 °C, 310 K)

8.3 Calculate the increase in the length of an aluminum bar 2 m long when heated from 0°C to 20°C. If the thermal coefficient of linear expansion of aluminium is 2.5×10^{-5} K^{-1}. (0.1cm)

8.4 A balloon contains 1.2 m^3 air at 15 °C. Find its volume at 40 °C. Thermal coefficient of volume expansion of air is 3.67×10^{3} K^{-1}.
(1.3 m^3)

8.5 How much heat is required to increase the temperature of 0.5 kg of water from 10 °C to 65 °C?
(115500 J)

8.6 An electric heater supplies heat at the rate of 1000 joule per second. How much time is required to raise the temperature of 200 g of water from 20 °C to 90 °C? (58.8 s)

8.7 How much ice will melt by 50000 J of heat? Latent heat of fusion of ice = 336000 J kg^{-1}.
(150 g)

8.8 Find the quantity of heat needed to melt 100g of ice at -10 °C into water at 10 °C. (39900 J)

(Note: Specific heat of ice is 2100 $Jkg^{-1}K^{-1}$, specific heat of water is 4200 $Jkg^{-1}K^{-1}$, Latent heat of fusion of ice is 336000 Jkg^{-1}).

8.9 How much heat is required to change 100 g of water at 100°C into steam? (Latent heat of vaporization of water is 2.26×10^6 Jkg^{-1}. (2.26×10^5 J)

8.10 Find the temperature of water after passing 5 g of steam at 100 °C through 500 g of water at 10 °C. (16.2°C)

(Note: Specific heat of water is 4200 $Jkg^{-1}K^{-1}$, Latent heat of vaporization of water is 2.26×10^6 Jkg^{-1}).

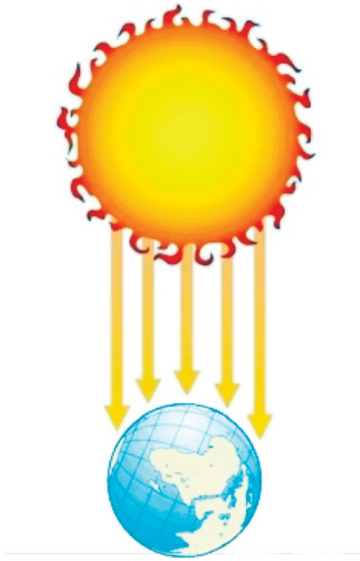
Unit 9

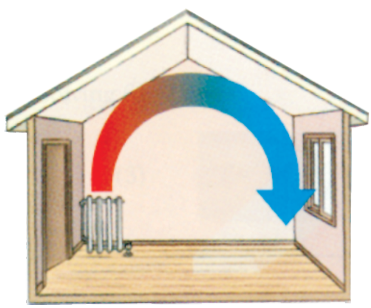
Transfer of Heat

STUDENT'S LEARNING OUTCOMES

After studying this unit, the students will be able to:

- recall that thermal energy is transferred from a region of higher temperature to a region of lower temperature.
- describe in terms of molecules and electrons , how heat transfer occurs in solids.
- state the factors affecting the transfer of heat through solid conductors and hence, define the term Thermal Conductivity.
- solve problems based on thermal conductivity of solid conductors.
- write examples of good and bad conductors of heat and describe their uses.
- explain the convection currents in fluids due to difference in density.
- state some examples of heat transfer by convection in everyday life.
- explain that insulation reduces energy transfer by conduction.
- describe the process of radiation from all objects.
- explain that energy transfer of a body by radiation does not require a material medium and rate of energy transfer is affected by:
    - colour and texture of the surface
    - surface temperature
    - surface area





Conceptual Linkage.

This unit is built on

Modes of heat transfer

- Science-VII

This unit leads to:

Thermodynamics

- Physics-XI

INVESTIGATION SKILLS

The students will be able to:

- describe convection in water heating by putting a few pinky crystals in a round bottom flask.
- explain that water is a poor conductor of heat.
- investigate the absorption of radiation by a black surface and silvery surfaces using Leslie cube.
- investigate the emission of radiation by a black surface and silvery surfaces using Leslie cube.

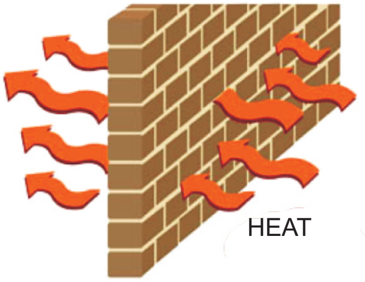
Major Concepts

9.1 The three process of heat transfer
9.2 Conduction
9.3 Convection
9.4 Radiation
9.5 Consequences and everyday applications of heat transfer

SCIENCE, TECHNOLOGY AND SOCIETY CONNECTION

The students will be able to:

- describe the use of cooking utensils, electric kettle, air conditioner, refrigerator cavity wall insulation, vacuum flask and household hot-water system as a consequence of heat transmission Processes.
- explain convection in seawater to support marine life.
- describe the role of land breeze and sea breeze for moderate coastal climate.
- describe the role of convection in space heating.
- identify and explain some of the everyday applications and consequences of heat transfer by conduction, convection and radiation.
- explain how the birds are able to fly for hours without flapping their wings and glider is able to rise by riding on thermal currents which are streams of hot air rising in the sky.
- explain the consequence of heat radiation in greenhouse effect and its effect in global warming.



Heat is an important form of energy. It is necessary for our survival. We need it to cook our food and to maintain our body temperature. Heat is also needed in various industrial processes. How to protect ourselves from high as well as low temperature, needs knowledge of how heat travels. In this unit, we will study various ways of heat transfer.

9.1 TRANSFER OF HEAT

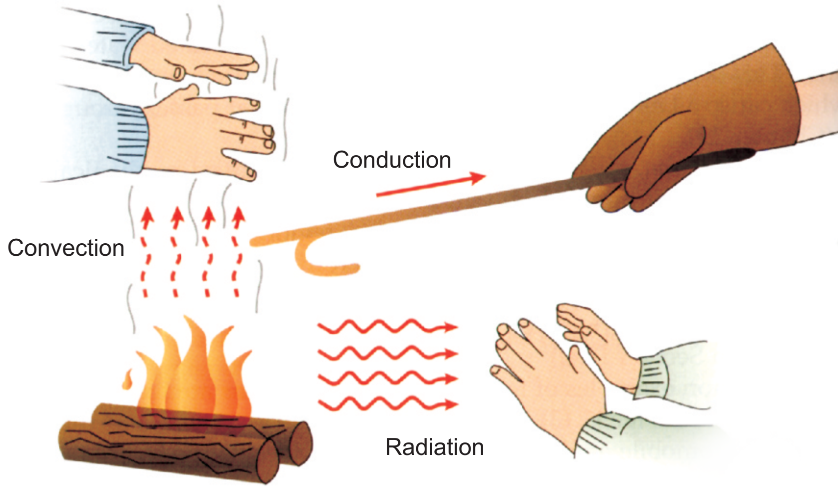


Figure 9.1: Three ways of heat transfer

Recall what happens when two bodies at different temperature are in thermal contact with each other. Thermal energy from a hot body flows to a cold body in the form of heat. This is called as transfer of heat. Transfer of heat is a natural process. It continues all the time as long as the bodies in thermal contact are at different temperature. There are three ways by which transfer of heat takes place. These are:

- conduction
- convection
- radiation

QUICK QUIZ

Think of objects around us getting heat or giving out heat.

9.2 CONDUCTION

The handle of metal spoon held in hot water soon gets warm. But in case of a wooden spoon, the handle does not get warm. Both the materials behave differently regarding the transfer of heat. Both metals and non-metals conduct heat. Metal are generally better conductors than non-metals.

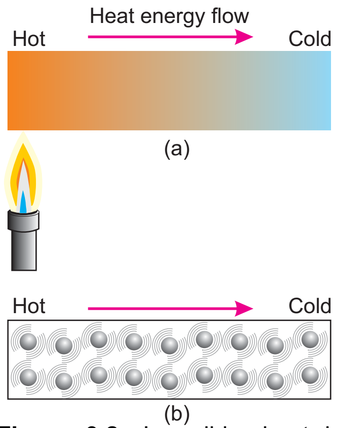


Figure 9.2: In solids, heat is transferred from one part to other parts from atoms to atoms or molecules to molecules due to collisions.

In solids, atoms and molecules are packed close together as shown in figure 9.2. They continue to vibrate about their mean position. What happens when one of its ends is heated? The atoms or molecules

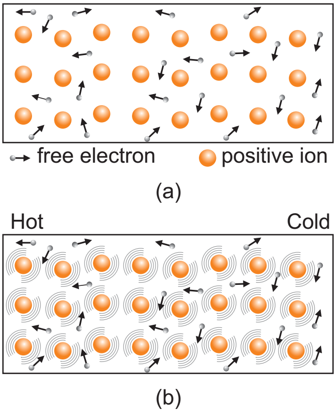


Figure 9.3: Conduction of heat in metals.

present at that end begin to vibrate more rapidly. They also collide with their neighbouring atoms or molecules. In doing so, they pass some of their energy to neighbouring atoms or molecules during collisions with them with the increase in their vibrations. These atoms or molecules in turn pass on a part of the energy to their neighbouring particles. In this way some heat reaches the other parts of the solids. This is a slow process and very small transfer of heat takes place from hot to cold parts in solids.

How does then heat flow from hot to cold parts in metals so rapidly than non-metals? Metals have free electrons as shown in figure 9.3. These free electrons move with very high velocities within the metal objects. They carry energy at a very fast rate from hot to cold parts of the object as they move. Thus, heat reaches the cold parts of the metal objects from its hot part much more quickly than non-metals.

The mode of transfer of heat by vibrating atoms and free electrons in solids from hot to cold parts of a body is called conduction of heat.

DO YOU KNOW?

Why Styrofoam boxes are used to keep food hot or ice cream cold for a long time? Styrofoam is a bad conductor of heat. It does not allow heat to leave or enter the box easily.

All metals are good conductors of heat. The substances through which heat does not conduct easily are called bad conductors or insulators. Wood, cork, cotton, wool, glass, rubber, etc. are bad conductors or insulators.

THERMAL CONDUCTIVITY

Conduction of heat occurs at different rates in different materials. In metals, heat flows rapidly as compared to insulators such as wood or rubber. Consider a solid block as shown in figure 9.4. One of its two opposite faces each of cross-sectional area A is heated to a temperature T_1. Heat Q flows along its length L to opposite face at temperature T_2 in t seconds.

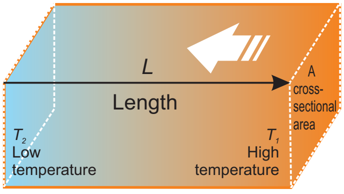


Figure 9.4: Rate at which heat conducts through different solids depends upon various factors.

The amount of heat that flows in unit time is called the rate of flow of heat.

Thus Rate of flow of heat $= \dfrac{Q}{t}$ .... (9.1)

It is observed that the rate at which heat flows through a solid object depends upon various factors.

CROSS-SECTIONAL AREA OF THE SOLID

Larger cross-sectional area *A* of a solid contains larger number of molecules and free electrons on each layer parallel to its cross-sectional area and hence greater will be the rate of flow of heat through the solid. Thus

Rate of flow of heat $\frac{Q}{t} \propto A$

LENGTH OF THE SOLID

Larger is the length between the hot and cold ends of the solid, more time it will take to conduct heat to the colder end and smaller will be the rate of flow of heat. Thus

Rate of flow of heat $\frac{Q}{t} \propto \frac{1}{L}$

TEMPERATURE DIFFERENCE BETWEEN ENDS

Greater is the temperature difference T_1 - T_2 between hot and cold faces of the solid, greater will be the rate of flow of heat. Thus

Rate of flow of heat $\frac{Q}{t} \propto (T_1 - T_2)$

Combining the above factors, we get

$$\frac{Q}{t} \propto \frac{A\,(T_1 - T_2)}{L}$$

Rate of flow of heat $\frac{Q}{t} = \frac{k\,A\,(T_1 - T_2)}{L}$ ... ... (9.2)

Here k is the proportionality constant called thermal conductivity of the solid. Its value depends on the nature of the substance and is different for different materials. From equation (9.2), we find k as:

$$k = \frac{Q}{t} \times \frac{L}{A\,(T_1 - T_2)} \quad \dots \quad \dots \quad \dots \quad (9.3)$$

Thus, thermal conductivity of a substance can be defined as:

The rate of flow of heat across the opposite faces of a metre cube of a substance maintained at a temperature difference of one kelvin is called the thermal conductivity of that substance.

Thermal conductivities of some substances are given in the table.

Thermal conductivities of some common substances

Substance	$Wm^{-1}K^{-1}$
Air (dry)	0.026
Aluminium	245
Brass	105
Brick	0.6
Copper	400
Glass	0.8
Ice	1.7
Iron	85
Lead	35
Plastic foam	0.03
Rubber	0.2
Silver	430
Water	0.59
Wood	0.08

USE OF CONDUCTORS AND NON-CONDUCTORS

In houses, good thermal insulation means lower consumption of fuel. For this, following measures may be taken to save energy.

- Hot water tanks are insulated by plastic or foam lagging.
- Wall cavities are filled with plastic foam or wool.
- Ceiling of rooms is covered by insulating materials (false ceiling).
- Double glazed window panes are used. These window panes have air between glass sheets that provides good insulation.

Good conductors are used when quick transfer of heat is required through a body. Thus cookers, cooking plate, boiler, radiators and condensers of refrigerators, etc. are made of metals such as aluminum or copper. Similarly, metal boxes are used for making ice, ice cream, etc.

Insulators or bad conductors are used in home utensils such as handles of sauce-pans, hot plates, spoons, etc. They are made up of wood or plastic. Air is one of the bad conductors or best insulator. That is why cavity walls i.e. two walls separated by an air space and double glazed windows keep the houses warm in winter and cool in summer. Materials which trap air i.e. wool, felt, fur, feathers, polystyrenes, fibre glass are also bad conductors. Some of these materials are used for laggings to insulate water pipes, hot water cylinders, ovens, refrigerators, walls and roofs of houses. Woollen cloth is used to make warm winter clothes.

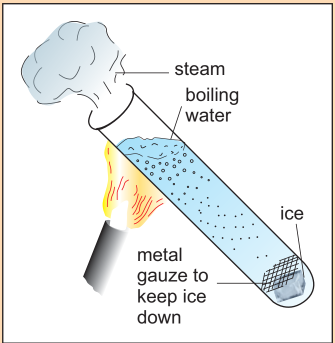
EXAMPLE 9.1

The exterior brick wall of a house of thickness 25 cm has an area 20 m^2. The temperature inside the house is 15°C and outside is 35°C. Find the rate at which thermal energy will be conducted through the wall, the value of k for bricks is 0.6 $Wm^{-1} K^{-1}$.

SOLUTION

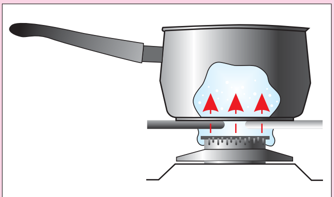
Here $A = 20\ m^2$

FOR YOUR INFORMATION



Water is a poor conductor. Water at the top in the test tube starts boiling after getting heat from the burner without melting ice.

DO YOU KNOW?



Sauce-pans are made of metal for quick heat transfer.

Figure 9.5: Soft insulation board between external brick wall of a house.

$L = 25\text{ cm} = 0.25\text{ m}$

$T_1 = 35 + 273 = 308\text{ K}$

$T_2 = 15 + 273 = 288\text{ K}$

$\Delta T = T_1 - T_2$

$= 308\text{ K} - 288\text{ K} = 20\text{ K}$

$k = 0.6\text{ Wm}^{-1}\text{K}^{-1}$.

Using equation 9.2, rate of conduction of thermal energy is

$$= \frac{k\,A\,(T_1 - T_2)}{L}$$

$$= \frac{0.6\ \text{Wm}^{-1}\text{K}^{-1} \times 20\ \text{m}^2 \times 20\ \text{K}}{0.25\ \text{m}}$$

$= 960$ watt or 960 Js^{-1}

Thus, the rate of flow of thermal energy across the wall will be 960 joules per second.

9.3 CONVECTION

Liquids and gases are poor conductors of heat. However, heat is transferred through **fluids** (liquids or gases) easily by another method called convection.

Why a balloon inflated with hot air as shown in figure. 9.6 rises up? A liquid or a gas becomes lighter (less dense) as it expands on heating. Hot liquid or gas rises up above the heated area. The cooler liquid or gas from the surroundings fills the place which in turns is heated up. In this way, all the fluid is heated up. Therefore, transfer of heat through fluids takes place by the actual movement of heated molecules from hot to cold parts of the fluid.

Transfer of heat by actual movement of molecules from hot place to a cold place is known as convection.

EXPERIMENT 9.1

Take a beaker and fill two-third of it with water. Heat the beaker by keeping a burner below it. Drop two or three crystals of potassium permanganate in the water. It will be seen that coloured streaks of water formed by the crystals move upwards above the flame

DO YOU KNOW?

Feathers give good thermal insulation especially when fluffed up.

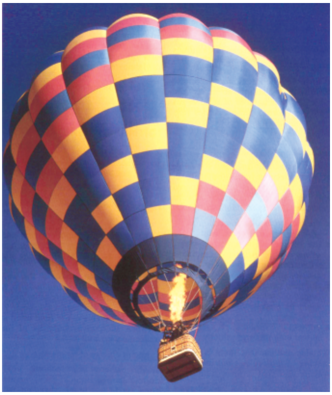


Figure 9.6: Balloons inflated with hot air rise up. Air becomes lighter on heating.

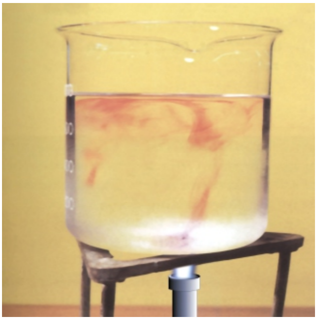


Figure 9.7: Crystals of potassium permanganate are used to show the movement of water on heating.

and then move downwards from side ways as shown in the figure 9.7. These coloured streaks show the path of currents in the liquid. Why the liquid currents stop on removing the burner under the beaker? When the water at the bottom of the beaker gets hot, it expands, becomes lighter and rises up. While the cold but denser water moves downward to take its place.

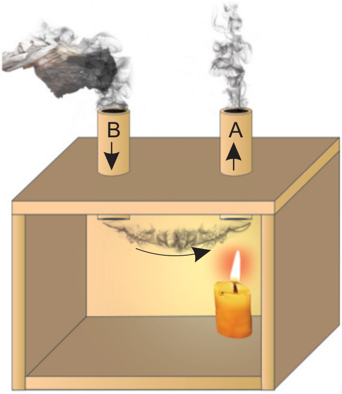


Figure 9.8: Smoke showing the path of the convection.

CONVECTION CURRENTS IN AIR

Gases also expand on heating, thus convection currents are easily set up due to the differences in the densities of air at various parts in the atmosphere. This can be observed by a simple experimental set up as shown in figure 9.8. Can you explain it?

USE OF CONVECTION CURRENTS

Convection currents set up by electric, gas or coal heaters help to warm our homes and offices. Central heating systems in buildings work on the same principle by convection. Convection currents occur on a large scale in nature. The day–to–day temperature changes in the atmosphere result from the circulation of warm or cold air that travels across the region. Land and sea breezes are also the examples of convection currents.

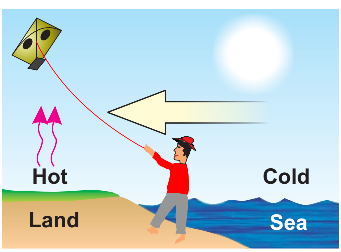


Figure 9.9: Sea breeze blows from sea to land in daytime.

LAND AND SEA BREEZES

Why does sea breeze blow during the day? Why does land breeze blow in the night?

Land and sea breezes are the result of convection. On a hot day, the temperature of the land increases more quickly than the sea. It is because the specific heat of land is much smaller as compared to water. The air above land gets hot and rises up. Cold air from the sea begins to move towards the land as illustrated in figure 9.9. It is called sea breeze.

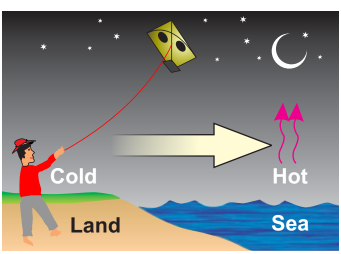


Figure 9.10: Land breeze blows from land to sea during night.

At night, the land cools faster than the sea. Therefore, air above the sea is warmer, rises up and the cold air from the land begins to move towards the sea as illustrated in figure 9.10. It is called land breeze.

How do the land and sea breezes help to keep the temperature moderate in coastal areas?

GLIDING

What causes a glider to remain in air?

A glider such as shown in figure 9.11 looks like a small aeroplane without engine. Glider pilots use upward movement of hot air currents due to convection of heat. These rising currents of hot air are called **thermals.** Gliders ride over these thermals. The upward movement of air currents in thermals help them to stay in air for a long period.

Figure 9.11: A glider

How do thermals help birds to fly for hours without flapping their wings?

The birds stretch out their wings and circle in these thermals. The upward movement of air helps birds to climb up with it. Eagles, hawks and vultures are expert **thermal climbers.** After getting a free lift, birds are able to fly for hours without flapping their wings. They glide from one thermal to another and thus travel through large distances and hardly need to flap their wings.

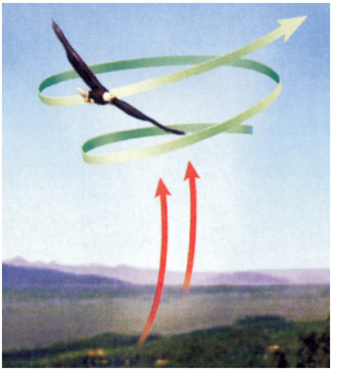


Figure 9.12: Birds fly taking the advantage of thermal air currents.

9.4 RADIATION

Our Sun is the major source of heat energy. But how does this heat energy reach the Earth? It reaches us neither by conduction nor by convection, because the space between the Sun and the Earth's atmosphere is empty. There is a third mode called radiation by which heat travels from one place to another. It is through radiation that heat reaches us from the Sun.

Radiation is the mode of transfer of heat from one place to another in the form of waves called electromagnetic waves.

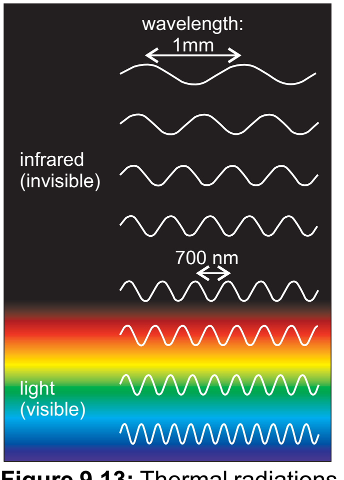


Figure 9.13: Thermal radiations and visible light spectrum.

How does this heat reach us directly from a fireplace? Figure 9.14 shows a fireplace such as used for room heating. Heat does not reach us by conduction through air from a fireplace because air is a poor conductor of heat. Heat does not reach us by

Figure 9.14: Heat from the fireplace reaches us by radiation.

convection because the air getting heat from the fireplace does not move in all directions. Hot air moves upward from the fireplace. Heat from the fireplace reaches us directly by a different process in the form of waves called radiation. A sheet of paper or cardboard kept in the path of radiations stop these waves to reach us.

Radiations are emitted by all bodies. The rate at which radiations are emitted depends upon various factors such as

- Colour and texture of the surface
- Surface temperature
- Surface area

Why does a cup of hot tea become cold after sometime? Why does a glass of chilled water become hot after sometime?

All the objects, lying inside a room including the walls, roof and floor of the room are radiating heat. However, they are also absorbing heat at the same time. When temperature of an object is higher than its surroundings then it is radiating more heat than it is absorbing. As a result, its temperature goes on decreasing till it becomes equal to its surroundings. At this stage, the body is giving out the amount of heat equal to the amount of heat it is absorbing.

When temperature of an object is lower than its surroundings, then it is radiating less heat than it is absorbing. As a result, its temperature goes on increasing till it becomes equal to its surroundings. The rate at which various surfaces emit heat depends upon the nature of the surface. Various surfaces can be compared using Leslie's cube.

Emission and Absorption of Radiation

A Leslie cube is a metal box having faces of different nature as shown in figure 9.15. The four faces of Leslie's cube may be as follows:

- A shining silvered surface
- A dull black surface
- A white surface
- A coloured surface

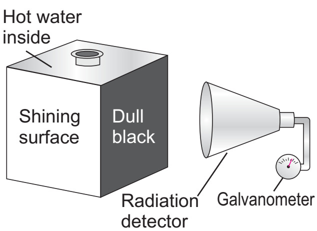


Figure 9.15: Radiations from Leslie's cube.

Hot water is filled in the Leslie's cube and is placed with one of its face towards a radiation detector. It is found that black dull surface is a good emitter of heat.

The rate at which various surfaces absorb heat also depends upon the nature of those surfaces. For example, take two surfaces, one is dull black and the other is a silver polished surface as shown in figure 9.16 with a candle at the middle of the surface. It is found that:

A dull black surface is a good absorber of heat as its temperature rises rapidly.

A polished surface is poor absorber of heat as its temperature rises very slowly. The observations made from the set up shown in figure 9.16 are shown in the table given below:

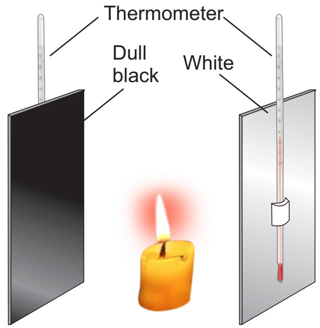


Figure 9.16: A comparison of absorption of radiation.

Surfaces	Emitter	Absorber	Reflector
dull black surface	best	best	worst
coloured surface	good	good	bad
White surface	bad	bad	good
shining silvered surface	worst	worst	best

It is also found that the transfer of heat by radiation is also affected by the surface area of the body emitting or absorbing heat. Larger is the area, greater will be the transfer of heat. It is due to this reason that large numbers of slots are made in radiators to increase their surface area.

GREENHOUSE EFFECT

How dos the temperature in a greenhouse can be maintained?

Light from the Sun contains thermal radiations (infrared) of long wavelengths as well as light and ultraviolet radiations of short wavelengths. Glass and transparent polythene sheets allow radiations of short wavelength to pass through easily but not long wavelengths of thermal radiations. Thus, a greenhouse becomes a heat trap. Radiations from the Sun pass easily through glass and warms up the objects in a greenhouse. These objects and plants such as

shown in figure 9.17give out radiations of much longer wavelengths. Glass and transparent polythene sheets

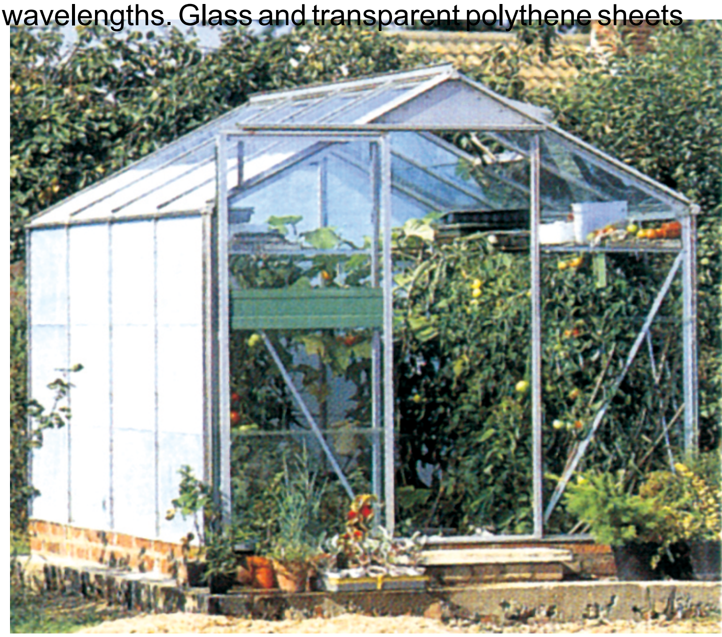


Figure 9.17: A greenhouse

do not allow them to escape out easily and are reflected back in the greenhouse. This maintains the inside temperature of the greenhouse. Greenhouse effect promises better growth of some plants.

Carbon dioxide and water also behave in a similar way to radiations as glass or polythene. Earth's atmosphere contains carbon dioxide and water vapours. It causes greenhouse effect as shown in figure 9.18 and thus maintains the temperature of the

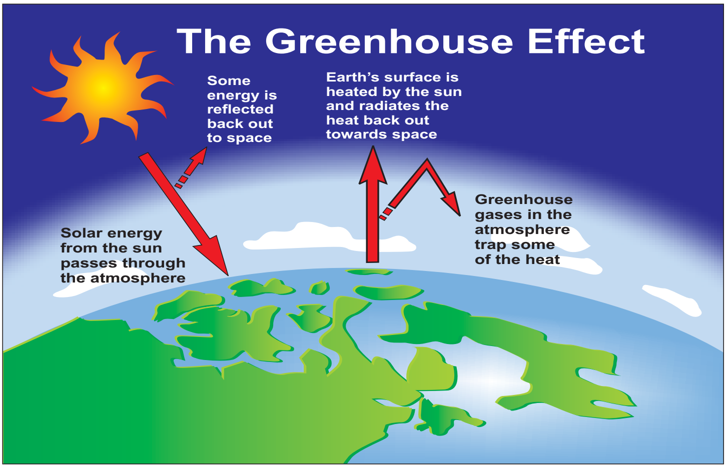


Figure 9.18: Greenhouse effect in global warming.

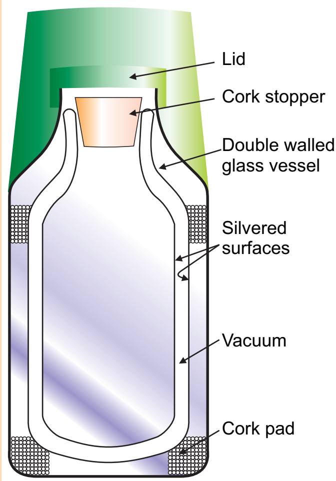
Earth. During the recent years, the percentage of carbon dioxide has been increased considerably. This has caused an increase in the average temperature of the Earth by trapping more heat due to greenhouse effect. This phenomenon is known as **global warming.** This has serious implications for the global climate.

9.5 APPLICATION AND CONSEQUENCES OF RADIATION

Different objects absorb different amounts of heat radiations falling upon them reflecting the remaining part. The amount of heat absorbed by a body depends upon the colour and nature of its surface. A black and rough surface absorbs more heat than a white or polished surface. Since good absorbers are also good radiators of heat. Thus, a black coloured body gets hot quickly absorbing heat reaching it during a sunny day and also cools down quickly by giving out its heat to its surroundings. The bottoms of cooking pots are made black to increase the absorption of heat from fire.

Like light rays, heat radiations also obey laws of reflection. The amount of heat reflected from an object depends upon its colour and nature of the surface. White surfaces reflect more than coloured or black surfaces. Similarly, polished surfaces are good reflectors than rough surfaces and reflection of heat radiations is greater from polished surfaces. Hence, we wear white or light coloured clothes in summer which reflect most of the heat radiation reaching us during the hot day. We polish the interior of the cooking and hot pots for reflecting back most of the heat radiation within them.

FOR YOUR INFORMATION



In a thermos flask, most of the heat is prevented to enter or leave the flask. This is done by suitable measures to reduce the transfer of heat due to conduction, convection and radiation. Thus, anything kept in it, maintains its temperature for a long time.

SUMMARY

- Heat flows from a body at higher temperature to a body at lower, temperature.
- There are three ways of heat transfer. These are conduction, convection and radiation.

- The mode of transfer of heat by vibrating atoms and free electrons in solids from hotter to colder part of a body is called conduction of heat.
- The amount of heat that flows in unit time is called the rate of flow of heat.
- The rate at which heat flows through solids depends on the cross-sectional area of the solid, length between hot and cold ends, temperature difference between hot and cold ends and nature of the material.
- The rate of flow of heat across the opposite faces of a metre cube maintained at a difference of 1 K is called the thermal conductivity of the material of the cube.
- Good conductors are used for quick transfer of heat. Thus cookers, cooking plate, boiler, radiators and condensers of refrigerators etc. are made of metals.
- Water is a poor conductor of heat.
- Materials which trap air are also bad conductors such as wool, felt, fur, feathers, polystyrenes and fibre glass.
- Transfer of heat by actual movement of molecules from hot place to a cold place is known as convection.
- Land and sea breezes are also the examples of convection.
- Gliders use upward movement of hot air currents due to convection of heat. Air currents help them to stay in air for a long period.
- Birds are able to fly for hours without flapping their wings due to the upward movement of air currents.
- The term radiation means the continual emission of energy from the surface of a body in the form of electromagnetic waves.
- Radiations are emitted by all bodies. The rate at which radiations are emitted depends on various factors such as colour and texture of the surface, temperature and surface area.
- A dull black surface is a good absorber of heat as its temperature rises rapidly.
- A polished surface is poor absorber of heat as its temperature rises very slowly.
- Radiations from the Sun pass easily through glass/polythene and warms up the materials inside a greenhouse. The radiations given out by them are of much longer wavelengths. Glass/polythene does not allow them to escape out and thus maintains the inside temperature of the greenhouse.
- Earth's atmosphere contains carbon dioxide and water vapours. It causes greenhouse effect and thus retains the temperature of the Earth.
- The bottoms of cooking pots are made black to increase the absorption of heat from fire.
- White surfaces reflect more heat than coloured or black surfaces. Similarly, polished surfaces are good reflectors than rough surfaces and reflection of heat radiations is

greater from polished surfaces. Therefore, We wear white or light coloured clothes in summer

- We polish the interior of the cooking pots for reflecting back most of the heat radiation inside the hot pots.
- A thermos flask consists of a double-walled glass vessel. It reduces the transfer of heat by conduction, convection and radiation.

QUESTIONS

9.1 Encircle the correct answer from the given choices:

i. In solids, heat is transferred by:
(a) radiation
(b) conduction
(c) convection
(d) absorption

ii. What happens to the thermal conductivity of a wall if its thickness is doubled?
(a) becomes double
(b) remains the same
(c) becomes half
(d) becomes one fourth

iii. Metals are good conductor of heat due to the:
(a) free electrons
(b) big size of their molecules
(c) small size of their molecules
(d) rapid vibrations of their atoms

iv. In gases, heat is mainly transferred by
(a) molecular collision
(b) conduction
(c) convection
(d) radiation

v. Convection of heat is the process of heat transfer due to the:
(a) random motion of molecules
(b) downward movement of molecules
(c) upward movement of molecules
(d) free movement of molecules

vi. False ceiling is done to
(a) lower the height of ceiling
(b) keep the roof clean
(c) cool the room
(d) insulate the ceiling

vii. Rooms are heated using gas heaters by
(a) Conduction only
(b) Convection and radiation
(c) Radiation only
(d) Convection only

viii. Land breeze blows from
(a) sea to land during night
(b) sea to land during the day
(c) land to sea during night
(d) land to sea during the day

ix. Which of the following is a good radiator of heat?

(a) a shining silvered surface

(b) a dull black surface

(c) a white surface

(d) green coloured surface

9.2 Why metals are good conductors of heat?

9.3 Explain why:

(a) a metal feels colder to touch than wood kept in a cold place?

(b) land breeze blows from land towards sea?

(c) double walled glass vessel is used in thermos flask?

(d) deserts soon get hot during the day and soon get cold after sunset?

9.4 Why conduction of heat does not take place in gases?

9.5 What measures do you suggest to conserve energy in houses?

9.6 Why transfer of heat in fluids takes place by convection?

9.7 What is meant by convection current?

9.8 Suggest a simple activity to show convection of heat in gases not given in the book.

9.9 How does heat reach us from the Sun?

9.10 How various surfaces can be compared by a Leslie cube?

9.11 What is greenhouse effect?

9.12 Explain the impact of greenhouse effect in global warming.

PROBLEMS

9.1 The concrete roof of a house of thickness 20 cm has an area 200 m^2. The temperature inside the house is 15 °C and outside is 35°C. Find the rate at which thermal energy will be conducted through the roof. The value of k for concrete is 0.65 $Wm^{-1}K^{-1}$. ($13000\ Js^{-1}$)

9.2 How much heat is lost in an hour through a glass window measuring 2.0 m by 2.5 m when inside temperature is 25 °C and that of outside is 5°C, the thickness of glass is 0.8 cm and the value of k for glass is 0.8$Wm^{-1}K^{-1}$? ($3.6x10^7 J$)